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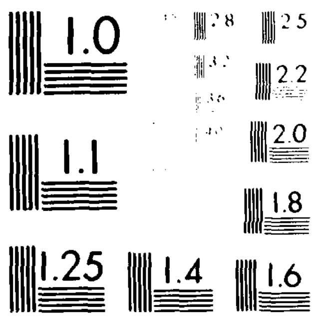

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ANNUAL PROGRESS REPORT 1978-79

August, 1979

Submitted by: R. T. Chien
G. G. Judge
H. V. Krone

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COORDINATED SCIENCE LABORATORY
SUMMARY OF
PROGRESS REPORT FOR JULY 1978 THROUGH JUNE 1979

1. Molecular Beam Epitaxy

GaAs and $Al_xGa_{1-x}As$ layers were grown by MBE and the electrical properties of these layers were characterized. GaAs layers with net electron concentrations below 5×10^{14} cm^{-3} exhibited 78^oK mobilities of about 105,000 cm^2/V-sec. High resistivity expitaxial layers of GaAs and $Al_xGa_{1-x}As$ were obtained by Cr-doping and sheet resistivities of above $10^5 \Omega/\square$ were achieved. $Al_xGa_{1-x}As$ layers doped with tin were also grown and electron mobilities of about 900 cm^2/V-sec associated with a 0.20 AlAs mole fraction and a net electron concentration of about 2×10^{18} cm^{-3} were achieved. In addition, GaAs/AlAs and GaAs/AlGaAs superlattices were grown and Raman experiments were made; the results showed no evidence of folding effects. These results can be explained on the basis of a phenomenological theory that was developed.

2. Semiconductor Materials and Devices

The hydride (H_2-HCl-In-PH_3) technique for the vapor phase epitaxial growth of InP is being studied to evaluate the potential of this method for the growth of high-purity material for optical and microwave device applications. The influence of system parameters such as HCl flow rates over the In-melt, substrate orientation, growth rate, partial pressure of H_2O, HCl, and O_2 in the growth zone are being investigated to determine the optimum conditions for high purity growth.

3. Quantum Electronics

The general thrust of the quantum electronics work reported here is the study of the excited states of atoms and molecules and energy transfer processes that occur.

The research reported in Section 3.2 is concerned with the excitation of excited states of molecules and the development of diagnostic methods to study their behavior.

The problem of interest in Section 3.3 is the measurement of the ionization coefficient in Ar, Kr and Xe versus E/N using a swarm chamber.

Experimental behavior could be attributed to two contributions, one associated with direct ionization and the other with metastables in the form of photoelectron emission.

Plasma etching with CF_4 is described in Section 3.4. It is shown that the etch rate does not follow the 704 nm fluorescence from F very well but does scale with electron density. Work on NF_3, which appears to etch much faster than CF_4, is also being pursued.

4. Semiconductor Physics

The work of the last year involved basic studies of semiconductor material properties, development of improvements in ion implantation and annealing, and applications to devices. The existing methods of deep-level transient spectroscopy have been extended to study junctions with significant leakage current. The continuing study of ion-implanted compound semiconductors has been applied to the development of avalanche photodetectors in GaAs and InGaAsP.

Theoretical studies have been devoted to transport in MOS structures. Here considerable emphasis has been placed on remote and confined scattering mechanisms by impurities and phonons. These investigations have also been applied to study effects of high fields on impurity scattering, and real space transfer between layers in multilayer heterojunction devices.

5. Thin Film Physics

The initial objective of this program was to investigate ion-surface interactions which have a controlling effect on the nucleation and growth kinetics, chemistry, and physical properties of alloy semiconducting films grown by sputtering. This objective has been broadened somewhat during the past year due to the surprisingly strong effects on elemental sticking probabilities, enhanced diffusion, and surface reactivity which we have observed during low energy ion bombardment of growing film surfaces. Such effects are quite general in nature and equally applicable to film growth by other vapor phase techniques, such as MBE, as well as to catalyzing surface reactions such as occur during reactive ion etching. In addition, the use of low energy ion bombardment effects to stablize new non-equilibrium structures has been pursued.

Analytical models have been developed to predict ion bombardment enhanced diffusion and elemental sticking probability effects. The calculated results have been supported by experimental measurements using newly developed and highly sensitive techniques. The results of these investigations have been used to grow GaSb single crystals with some of the lowest reported carrier concentrations and to isolate the Sb vacancy level. Finally, these effects have also been used to allow the growth of stable single crystal non-equilibrium structures such as $InSb_{1-x}Bi_x$ and $(GaSb)_{1-x}Ge_x$ alloys which have unusual properties and cannot be grown by other methods.

6. Microwave Acoustics

The microwave acoustic research objective is to originate and analyze new principles that will lead to significant device applications. Work has been directed toward the realization of a new class of devices based on the propagation of nondispersive line acoustic waves along the edge of cleaved substrates. Line Acoustic Waves are being studied in the substrate GaAs to investigate wave-charge carrier interactions. In particular, the possibility of the synchronous transport of charge using the traveling wave electric field of LAW is of interest. A new theoretical approach has been derived to analyze the effect of electrically loaded structures on a surface acoustic wave propagation path. This work has led to a theoretically derived scatter matrix for a single element which includes elastic or piezoelectric loading effects. The single element analysis has been extended to calculate the response and electrostatic charge distribution of SAW interdigital transducers with floating electrodes, missing electrodes and randomly placed electrodes. The major advantage of this work is that it replaces a complex field problem with a simple circuit model.

7. Surface Studies

Work has continued on studying the mechanism of surface layer formation from polyatomic molecules. Direct laser excitation of the gas has so far not achieved any observable changes. However, detailed measurements on isotopically different gases have revealed large differences

in decomposition rate. Studies of individual atomic jumps in surface diffusion have also been initiated. These have already revealed hitherto unknown details about ordinary 1-D diffusion, as well as about atomic jumps across close packed atom rows.

8. Electromagnetic Communication, Radiation and Scattering

Significant progress has been made in the design and characterization of both active and passive components for millimeter wave integrated circuits. Specifically, radius waveguide transitions, probes and frequency scannable antennas were developed while oscillater design was modified for higher frequencies. Theoretical methods for analyzing dielectric waveguides were developed.

The Fourier transform approach has been extensively used in solving electromagnetic radiation and scattering problems. Iterative methods for systematically improving a given asymptotic solution have been devised and new accuracy tests developed and applied.

9. Plasma Physics

Measurements of the one and two point probability distribution of potential fluctuations in an unstable plasma have revealed the general non-gaussian character of the turbulent field. A system has been constructed for rapidly pulsing the drift velocity of the discharge for time resolved measurements.

10. Rarefied Gas Dynamics

Under our long range plans to use the kinetic theory approach to solve gas dynamics problems under non-equilibrium conditions, we have solved the Boltzmann and the Krook equations for evaporation and condensation problems. These solutions exhibit non-equilibrium behavior of the vapor significant to the study of the evaporation and condensation phenomena. Some of the results are in good agreement with available experiments. We have also developed simple kinetic theory approaches that can be used together with continuum methods to calculate the evaporation and condensation flow parameters as well as the ensuing flow field.

11. Computational Gas Dynamics

Under our long range plans to solve directly the basic gas dynamic equations for complex problems, we have studied the application of finite element, finite difference and hybrid methods to solve selected problems of current interest. Two methods have been developed to generate numerically optimum meshes that can be used to implement both finite element and finite difference methods for problems of complex geometries. We have also developed a hybrid method to solve the nonlinear free surface wave problems with a finite computational domain and an open boundary.

12. Fault-Tolerant Systems and Computer Architecture

Research in Fault-Tolerant Distributed Systems includes the design, modeling, and performance evaluation of loosely coupled, fault-tolerant distributed systems as well as techniques to test the units of a system in order to detect faulty units.

Research in Computer Architecture includes the study of the performance of functional resources used by a multiple-stream pipelined processor, a comparative analysis of parallel computer architectures, a comparison of data flow architectures, and the study of high level language oriented computer architectures.

Research in Computer System Organization includes the modeling of multiple processor virtual memory systems, the performance evaluation of multiple processor systems with shared memory using the AMP-1 system, and the study of cost effective parallel processor design.

Research in Problem-Oriented Architectures includes the performance evaluation of conventional algorithms using multiple instruction stream processing on the AMP-1, and a study of efficient computer structures for 2D Fast Fourier Transform computation.

Research in Modeling and Evaluation of Large Computer Systems includes the simulation of multiple instruction stream machines, the continuing study of queueing networks exhibiting "local balance," and the performance measurement and evaluation of large scale computer systems from system accounting files.

13. Display, Memory, and Computer Terminal Research

The characteristics of professional teleconferencing are being examined to clarify those concepts important for effective graphic communication over low bandwidth channels. A minicomputer based test facility is being used to simulate communications channel operation. These simulations have shown that voice, image data, and a remote pointer can be combined on a single low bandwidth digital voice channel.

An optical disk memory system suitable for low cost terminal-based mass storage is being developed. Recent advances include new control strategies for the laser beam tracking servo system.

A mini-computer controlled real-time curve tracer is being used to investigate the electrical characteristics of the AC plasma display panel. With this instrument we have discovered a new memory mechanism that accounts for 60% of the memory margin.

14. Applied Computation Theory

During the past year we have continued our investigations in the area of the design and analysis of computations. We have pursued our well-established research in computational geometry, where a variety of planar problems have been solved, and in parallel computation, where new promising avenues of considerable practical significance have been opened. In addition, new interesting studies have been undertaken. In the area of combinatorial problems, we have studied two-dimensional bin packing, database organization, matching, and generation of permutations. The important relationship between computation time and available storage has been analyzed for a number of problems.

15. Advanced Automation

Research progress has been made in a number of areas, including manipulation and assembly, visual information processing and recognition, computer aided decision making, natural language access to a large database, database browsing, automatic planning, natural language understanding, human decision making and human-computer interaction. Work continued on a mechanical arm system which uses computer vision and force feedback sensors

for positioning. We developed an extensive bottom-up artifact modeling and recognizing system, and we investigated feature network matching and parallel methods for picture processing and computer vision. Research continued on the conceptual design of two intelligent systems for enhancing safety in the cockpit of commercial airliners, and for locating faulty components in analog circuit boards. A new natural language system called JETS has been designed to interface users to a large database, and tools have been developed and used to evaluate PLANES, our old natural language database system. Within JETS, work has centered on the semantic interpretation of queries, and on the use of problem-solving methods for answering vague or complex questions. A system called BROWSER was developed to do automatic troubleshooting in databases which describe mechanical systems. PLANSYS, a flexible planning and problem-solving system, was programmed and tested. A program was implemented to generate visual analog representations for answering questions, given English sentences describing physical scenes. Methods have been developed for allocating decision-making functions between a pilot and a computer in an airborne environment. Experimental studies were performed on the effects of various factors on human fault diagnosis abilities. A queuing network model for analysis of library networks was developed and applied to an interlibrary loan network. Finally, new efforts were begun in automatic modeling of computer users and training simulation for the pilots of supertankers.

16. Information Retrieval Research

During the 1978-1979 time period the Information Retrieval Research Laboratory (IRRL) conducted a number of research and development projects and directed the operation of the University of Illinois' online search service. Major activities included the following: analysis of database data; design of an automatic database selector; design of an integrated man/machine interface to facilitate network resource utilization; provision of computer assistance in development of an index and bibliography of electro-organic synthesis reactions; development of a computer-readable database directory; and management and direction of the University of Illinois' online search service.

17. Communications

Progress is reported in three major research areas. First, new results have been obtained on the construction of efficient universal variable-rate source codes and bounds on the redundancy of universal variable-rate data compression schemes. We have also investigated several specific source codes including some composite codes and codes derived from a particular mixture probability distribution. Second, results have been obtained on digitization of signal detection systems and on the design of robust detectors and filters. We have also studied state estimation for uncertain systems and for linear systems driven simultaneously by Wiener and Poisson processes. Third, we have obtained new results on spread-spectrum multiple-access communication systems including binary direct-sequence and quadriphase direct-sequence systems, frequency-hop systems and hybrid frequency-hop/direct-sequence systems. We have also studied the performance of binary direct-sequence spread-spectrum communication systems for a general class of Rician fading channels. Several new results have been obtained on the construction of sequences with desirable correlation properties and on bounds for various correlation parameters.

18. Analog and Digital Circuits

In studies of reduced-order modeling of large-scale circuits, a partitioning algorithm has been derived relating to the tearing of large circuits into smaller subcircuits which promises to reduce analysis computation time. Work on automatic fault analysis of analog curcuits has concentrated on a large-change sensitivity method in which faulty components are identified from post-test calculations. Stress is placed on overcoming ambiguous results arising from large component tolerances. In the tuning of analog filters, a new algorithm has been found and successfully applied to a wide variety of analog filter designs. The method usually makes tuning possible with only two or three iterations. In studies of switched-capacitor filters, work has concentrated on the relationship of filter termination to stopband response, and a new design technique has been developed based on the bilinear z-transformation applied to the analog prototype. Two new computer programs have been completed. The first is used in analyzing switched-capacitor circuits; the second in the simulation of digital

filter structures to give sensitivity, noise and limit-cycle behavior. In studies of digital signal processing for synthetic aperture radar, work has concentrated on the inherent distortion of processing algorithms and in high-speed processor designs.

19. Decision and Control

Several projects have led to many results involving various aspects of control analysis, synthesis, and optimization. The key directions are control and decision strategies for systems with imperfect information, reduced order modeling by chained aggregation and by singular perturbation, control strategies for large scale systems with multiple decision makers, multimodeling of large scale systems, and well-posedness of model order reduction in multicriteria problems.

20. Population/Food/Weather Studies

The overall objective of the project is to develop and disseminate nationally, to institutions of higher education, multipurpose computer-based instruction models for teaching Population Dynamics and population-related issues. This objective is designed to fill a recognized need for the development of techniques to communicate the structure and dynamics of population by utilizing the latest developments in computer technology. It is a primary objective of the project to design a flexible interactive educational system which can be adapted and implemented on a large number of computer systems (graphics terminals, teletype, slide output, hardcopy output) throughout the nation.

The weather studies are aimed at developing long range forecasting techniques for weather and climate. The forecast range varies from a few months to a few years. In addition to the common meteorological variables, crop data has been found to be a useful indicator of long range weather trends.

1. MOLECULAR BEAM EPITAXY

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1.1 Introduction

The Molecular Beam Epitaxy Program is a broad-based investigation of MBE growth, characterization, and device development. A team of senior faculty is involved in this program, investigating various aspects of the problem. During the past year, while the MBE facility was being developed on campus, research was performed using MBE facilities at Bell Laboratories, and other research on MBE materials grown at Bell was performed on campus.

A Riber 1000 MBE system has now been received and installed in the Coordinated Science Laboratory (Fig. 1.1). Research involving this system will be reported in the next Progress Report.

1.2 MBE Growth of III-V Compounds*

During the past year, the growth and properties of Sn and Cr-doped GaAs and $Al_xGa_{1-x}As$ epitaxial layers by MBE have been investigated. A systematic effort was made to reduce the background carrier concentration and the oxygen contamination of GaAs layers during MBE growth. In addition to maintaining a very clean growth chamber, effusion cells were outgassed for a prolonged period of time. H_2O was found to predominantly affect MBE layers. We observed that, in addition to high purity starting materials and a high vacuum, the reduction of water vapor

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contracts DAAG-29-78-C-0016 and N00014-79-C-0424). Work at Bell Laboratories was supported by Bell Laboratories.

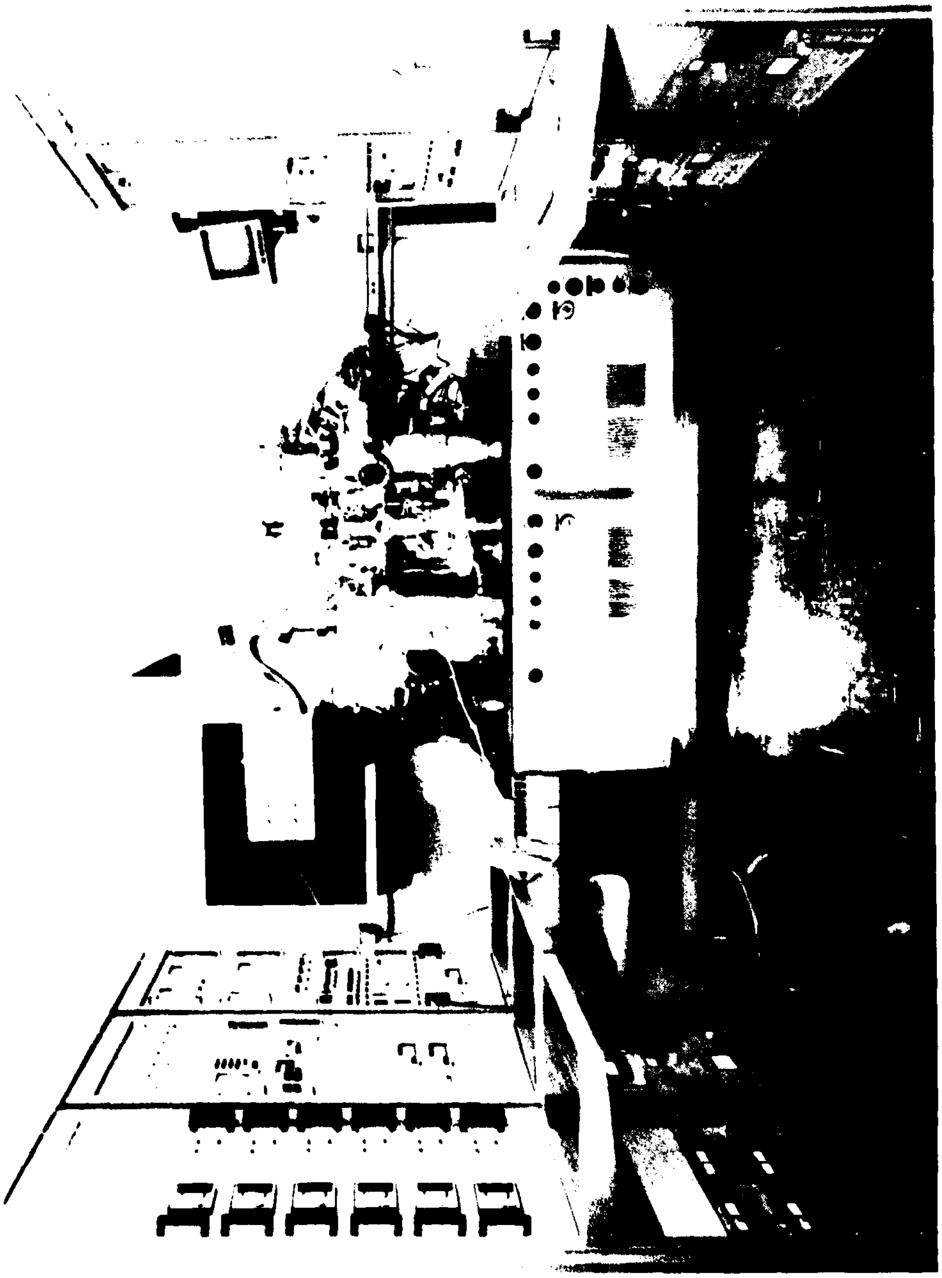

Fig. 1.1 Riber MBE-1000 Molecular Beam Epitaxy facility in the Coordinated Science Laboratory.

in the growth chamber was necessary to obtain high purity epitaxial layers. The room temperature and liquid nitrogen temperature mobilities of unintentionally doped p-type epitaxial layers were 450 and 8440 cm^2/V-sec., respectively. The net hole concentration at 298°K and 78°K were 7.8 X 10^{13} cm^{-3} and 2 X $10^{13} cm^{-3}$, respectively. GaAs epitaxial layers doped with Sn to a net electron concentration of less than 5 X $10^{14} cm^{-3}$ exhibited an electron mobility of 8080 and 105,000 cm^2/V-sec. at 298°K and 78°K, respectively. These are the highest mobility values reported anywhere. The reduction of water vapor was evidenced by the fact that the freeze-out ratio in the net electron concentration was only 1%.

Cr-doped epitaxial layers of GaAs and $Al_xGa_{1-x}As$ layers have also been grown because of their potential as buffer layers for high performance microwave FET's. A substrate growth temperature range of 500°C to 650°C was investigated. The results indicated a strong dependence on the substrate growth temperature for Cr incorporation. Above a certain critical limit for the Cr beam intensity, a degradation of surface morphology was observed. At substrate growth temperatures of 500°C, 580°C and 640°C, this limit in GaAs corresponds to Cr cell temperatures of 850°C, 900°C, and over 950°C, respectively. On the other hand, the minimum Cr cell temperature required for achieving semi-insulating properties showed the opposite dependence. To obtain semi-insulating properties and a good surface morphology, the substrate growth temperature had to be greater than about 560°C. Cr cell temperatures of at least 50° higher than those for GaAs were necessary to cause any surface degradation in $Al_{0.2}Ga_{0.8}As$ layers. Sheet resistances on the order of 10^9 Ω/square have been achieved both in GaAs and $Al_{0.2}Ga_{0.8}As$ layers if grown under the constraints mentioned above.

Transport properties of $Al_xGa_{1-x}As$ having AlAs mole fractions between 0.14 and 0.4 and grown by MBE were also investigated. The Al cell temperature was kept at 1075°C while the Ga cell temperature was varied between 910°C and 950°C to obtain the aforementioned AlAs mole fractions. The donor levels of Sn in $Al_xGa_{1-x}As$ obtained from the net donor concentration are below 3 meV, 30 meV and 40 meV for $x = 0.14$, $x = 0.29$, and $x = 0.375$, respectively. $Al_{0.22}Ga_{0.78}As$ layers having a net electron concentration of 1.7 X $10^{18} cm^{-3}$ and grown at 630°C exhibited a mobility of 868

and 1095 cm^2/V-sec at 300°K and 78°K. The mobility was found to be strongly dependent upon the substrate temperature during growth. The lower substrate temperatures resulted in lower mobility. Lowering the Sn cell temperature increased the electron mobility somewhat, but less than expected. This was attributed to high background compensation. $Al_{0.34}$-$Ga_{0.56}As$ films with a net electron concentration of $3 \times 10^{16} cm^{-3}$ showed an electron mobility of 975 cm^2/V-sec. at 298°K.

1.3 Raman Scattering in Superlattices: Search for Folding Effects and Anisotropy of Polar Phonons*

The folding of the electron energy bands caused by the new periodicity in multiple GaAs-$Ga_{1-x}Al_xAs$ heterostructures is now a phenomenon well established [1]. Electron-phonon scattering processes which are forbidden in the bulk materials because of wave vector conservation, may become allowed in the layered structure. In addition, folding effects are also to be expected in the phonon spectrum of a superlattice. Raman scattering (RS) is a valuable tool for studying these phenomena caused by the layering, which have important implications for the transport and optical properties of these novel materials.

Phonon-folding in superlattices has been reported in several publications by Merz et al. [2,3] at Bell Laboratories and Sai-Halasz et al. [4,5] at IBM. We have reexamined the question of zone folding in RS [6]. Two GaAs-AlAs superlattices with periods of 50 Å GaAs-50 Å AlAs and 14 Å GaAs-11 Å AlAs were investigated in this work. The results we have obtained can be summarized as follows:

(1) The profuse structure below ~ 220cm $^{-1}$ reported by Merz et al. [2,3] on the same 14-11Å sample, which they construed as evidence of phonon-folding is due to an experimental artifact

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arising from inadequate corrections for scattering from rotational modes of O_2 and N_2 in the air at the sample surface.

(2) For laser energies near the fundamental gap of the 14-11 Å sample the Raman spectra show two extra lines which exhibit the same selection rules and a resonant behavior similar to that of the 290 cm^{-1} peak reported by Sai-Halasz et al. [4,5] in Raman experiments on GaAs-$Ga_{0.75}Al_{0.25}As$ layered structures. In that work the extra phonon peak was ascribed to an Umklapp process in a scheme where the Brillouin zone was effectively folded for the electrons but not for the phonons [4,5]. On the basis of a phenomenological theory and moreover of Raman experiments done in the forward configuration on the 50-50 Å sample, we are able to show that the extra lines are simply due to the scattering from zone center LO phonons propagating parallel to the layers, i.e., with E symmetry in the tetragonal superlattice. The optical anisotropy induced by layering arises from the different boundary conditions for the electric field associated with the LO-phonons propagating parallel and perpendicular to the layers.

(3) The E(LO) modes can be observed in a scattering configuration where they should be forbidden because of wavevector conservation. We have shown that this has to be traced to the presence of defects or disorder in the superlattice. This opens up the possibility of using RS as a sensitive technique for the characterization of the samples.

1.4 Real-Space Electron Transfer in Superlattices*

A new class of devices employing real-space transfer of electrons between alternating layers of GaAs and AlGaAs has been described [7]. This work is presented in Section 4.4.3.

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2.1 Introduction

The primary goal of this research which was initiated during the past year is to evaluate the potential of the hydride (H_2-HCl-In-PH_3) growth technique for the growth of high-purity InP for optical and microwave device applications. Besides investigating the various growth parameters that can influence the purity of the grown layers, such as partial pressure of HCl, H_2O, and O_2 in the growth zone, HCl flow rates over the In-melt, growth rate, substrate orientations, etc., an important part of this work is characterizing the purity of the samples grown. The total ionized impurity concentration is studied through Hall coefficient measurements at 300^oK and at 77^oK. The origin and influence of growth conditions on acceptor concentrations are studied through low temperature photoluminescence measurements. With joint support from H. Lessoff of the Naval Research Laboratory a far infrared Fourier transform spectrometer has been set up for the study and identification of residual donor species in high-purity semiconductors. This facility will be used to study the donor impurities in InP grown using the hydride process when samples of sufficient purity are obtained.

2.2 Hydride Vapor Phase Growth of High-Purity InP*

With support by DARPA through ONR, we have been studying the use of the growth of InGaAsP quaternary using the hydride growth technique for applications in near infrared sources and detectors. A schematic

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contracts DAAG-29-78-C-0016 and N00014-79-C-0424 and by DARPA through ONR contract N00014-77-C-0086.

diagram of the vertical vapor phase reactor used for this work is shown in Figure 2.1, and this same reactor is also being used in the growth of high-purity InP. Although this design is much more complex than would be required for simply the growth of InP, the results obtained should be representative of those that can be expected in the growth of complex device structures. In conjunction with this research program the gas control system is being modified to provide fully automatic control but also, and more importantly the high-purity growth capability, to minimize the possibility of leaks. A schematic diagram of the automatic gas control system is shown in Figure 2.2. This gas flow system includes provisions for the addition of NH_3, O_2 and excess HCl into the reactor for the investigation of the influence of these gases on the purity of the epitaxial layers.

Preliminary growth runs using an earlier non-automatic gas control system resulted in uniform epitaxial InP layers with carrier concentration in the 8-12 x $10^{15}cm^{-3}$ range and room temperature and liquid nitrogen temperature mobilities of 3-4000 and 20-30,000 cm^2/V-sec respectively. The variation in growth rate, surface morphology, carrier concentration and mobility with III/V ratio, total gas flow, temperature, etc. have been studied using the old gas flow system and these studies will be extended with the new system to obtain the highest purity possible.

2.3 Fourier Transform Spectroscopy of Shallow Donor Levels*

With additional support from the Naval Research Laboratory (Howard Lessoff) and an Engineering Equipment Grant from the National Science Foundation, a far infrared Fourier transform spectrometer has been established for the study of shallow donor impurities in high-purity semiconductors. The detection and identification of impurities present in semiconductors in concentrations $\lesssim 10^{15}cm^{-3}$ (i.e., $\lesssim$ 0.01 ppm) is very difficult and often impossible using standard analytical techniques and

*This work was supported by the Naval Research Laboratory under contract N00173-78-C0129 and by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under contracts DAAG-29-78-C-0016 and N00014-79-C-0424 and by the National Science Foundation under Grant ENG-77-17739.

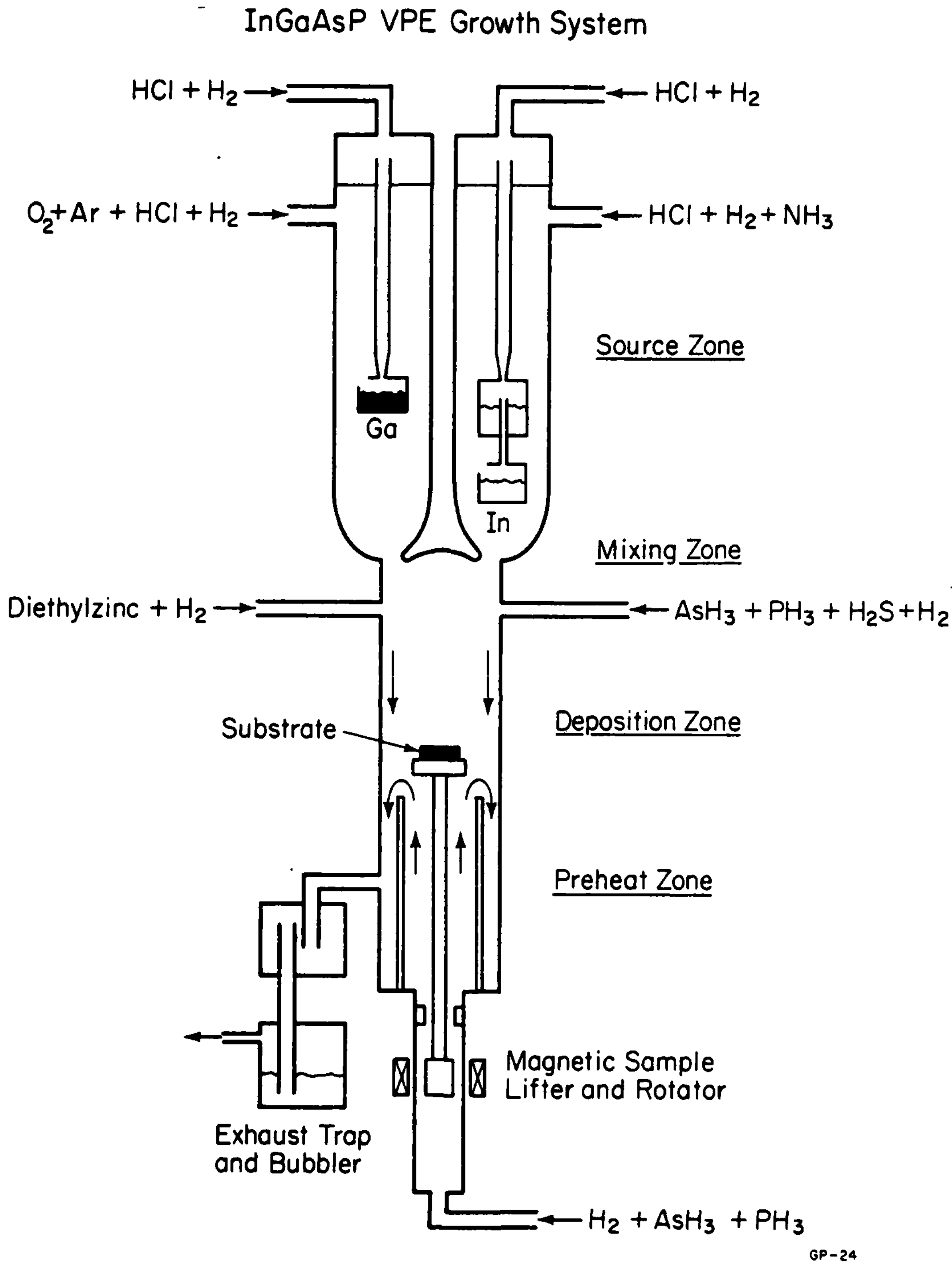

Fig. 2.1 Vertical vapor phase reactor schematic.

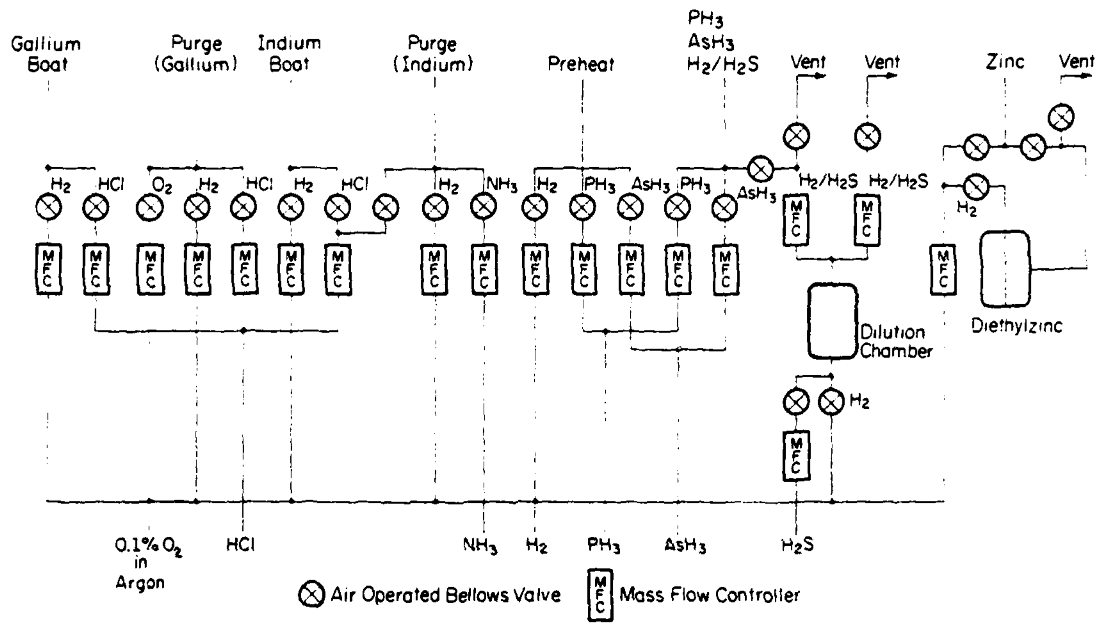

Fig. 2.2 Automatic Gas Flow Schematic.

readily available sample sizes. The total concentration of electrically active impurities can be determined from the analysis of Hall effect vs. temperature measurements, but this method does not permit the identification of the chemical species present, especially in III-V compound semiconductors or when multiple impurities are present. A very powerful technique which does permit the identification of chemical donor species in very-high-purity semiconductors is photothermal ionization spectroscopy. This technique consists of making extrinsic photoconductivity measurements at low temperatures such that most of the uncompensated impurities are neutral. For the shallow impurities in compound semiconductors these measurements must be made in the far infrared spectral region.

The photothermal ionization photoconductivity differs from ordinary extrinsic photoconductivity in that in a narrow temperature range photoconductivity results not only from photoionization of the impurity ground state but also from thermal ionization of carriers optically excited to the impurity states. Through this technique the energy separation between the ground and excited states can be measured very accurately. If the impurity states were hydrogenic this energy separation would be the same for all impurity atoms, but of course this is not the case. The small differences in ground state energies for different impurities permits the identification or at least detection of different impurity levels. For shallow donor levels in compound semiconductors the central cell corrections to the ground state energy is very small. However, the difference between the ground state energies of different impurities becomes greater in a magnetic field so Zeeman measurements through photothermal photoconductivity makes the detection of different impurities easier. A 65kG super conducting solenoid with a variable temperature sample space has been incorporated in the Fourier transform apparatus.

When InP samples of the required purity are grown using the hydride technique the residual impurities will be characterized using the above technique. The study of shallow donor impurities in InP grown by LPE and the PCl_3 VPE techniques under Contract N00173-79-C-0184 will be valuable in determining the residual impurities characteristics of the hydride growth system.

2.4 LPE Growth of InGaAsP*

The LPE growth of the quaternary alloy InGaAsP has been studied extensively in this work and the results obtained are described in detail in References 1-7. Some recent results in the growth of the ternary InGaAs lattice matched to InP substrates are particularly relevant to the growth of high-purity InP using the hydride technique. The high purity indium source material used for both systems must be further purified by baking before it is used to grow high purity layers. The optimum baking time and temperature for the indium is more easily determined in the LPE system and the results can be applied to the hydride system. The indium baking technique has been studied for growth of InGaAs on InP substrate by LPE. It has been shown that by baking the indium in a graphite boat in a hydrogen atmosphere at a temperature of 650°C that 24-48 hours of baking is required to purify the indium and that further baking will not improve the purity of the InGaAs layers grown using this indium.

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3.1 Excitation and Study of Highly-Excited States of Molecules

3.1.1 General Research Goals

Knowledge of molecular properties, of interest in quantum electronics, decreases rapidly as one goes up the energy "ladders" of the molecule. The overtone and combination bands, plus quasi-continuum of a molecule have received relatively little study compared to the ground states. It is the general goal of this research to study these excited states and evaluate their properties for use in quantum electronics.

To accomplish this task, two problems must be solved: a) develop methods of excitation for the excited states, and b) develop methods for diagnostics of the excited states. The method of excitation and diagnostics may be similar or different. Also methods for excitation and diagnostics for excited states will probably be different than those used for ground states of the molecule.

3.1.2 Search for and Evaluation of Excitation-Diagnostic Schemes

The general research goals stated above are very broad and complex and certainly could not be encompassed with the resources of this particular contract. Hence, time has been spent on an extensive literature search to evaluate existing techniques, devise and theoretically evaluate new techniques and seek a promising technique to converge on within our contract means.

The particular excitation and/or diagnostic schemes examined thus far are the following.

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3.1.3 Coherent Excitation and Probing

Coherent photon pumping and probing of molecules is one attractive method for studying excited states. The principal difficulty with this method is the availability of frequency tunable sources. With fixed frequency sources, one must find appropriate matches between the source and molecule. In principle, curve fitting transient analysis calculations and experimental data [1,2] would yield molecular parameters.

$^{14}NH_3$, excited with CO_2 and HF laser pumps and probed with K-band microwave signals, is being pursued [3,4].

3.1.4 Laser Induced Fluorescence

A molecule can be excited by one [4,5,6] or more [7]coherent photons to states that spontaneously fluoresce. A time-resolved observation of the spontaneous emission then provides data on the excited state populations.

For this method to be effective, there must again be a frequency match between pump and molecule, and the spontaneous radiation strong enough to detect. At the present time, this method has been used mainly to study the first vibrational states of the molecule which fluoresce in the IR.

Our study of several molecules indicates that this method will be difficult to apply to highly excited states and that frequency resolution will be difficult to obtain.

3.1.5 Multi-photon Excitation

Multi-photon pumping of molecules with strong CO_2 laser radiation can certainly excite high lying energy states of a molecule, in fact this pumping scheme can readily dissociate and/or ionize the molecule. Multi-photon pumping, along with coherent photon probing [8], have been used to study SF_6, CF_3I and CF_3Br. However, while transient molecular absorptions were observed, details of the absorptions were not pursued, and the absorbtion states not identified. Again the absorption states were probed with fixed frequency signals which limited what could be achieved.

Ambartsumyan, et al. [9] studied the excitation of NH_3 with an IR-UV double resonant technique which in principle could monitor the populations of overtone and combination states of the molecule. However,

only v = 1 was studied, primarily because of the low ultraviolet absorption.

It would appear that it would be worthwhile to excite a molecule via multi-photon pumping and probe over a range of frequencies with a tunable probe to obtain an absorption spectrum and also look for transient responses.

3.1.6 Electron Impact - Coherent Probe

Electron impact excitation can certainly excite high-lying energy states of a molecule, i.e., up to v = 37 or greater [10] in CO. Again one could probe the excited gas with a frequency tunable probe and look for absorptions and transients. Also one could add a coherent pump to achieve some frequency selectivity.

A preliminary experiment was tried on $^{14}NH_3$ in a DC discharge, wherein absorption was seen on the HF laser P(9) 1 → 0 line. Since this line absorption has not been seen in the ground states, it is concluded it is a hot band absorption.

3.2 Energy Transfer Processes in Excited Atoms

3.2.1 Experimental Apparatus and Technique

The experimental technique in which the ionization coefficient is deduced from the ratio of the integrated ion and electron currents in a pulsed drift tube apparatus is well established and documented [11]. The drift tube, shown in Fig. 3.1, was adapted from a design used for the measurements of drift velocity and is described elsewhere [12]. An electric field is established in the drift region by a voltage applied across a series of accurately spaced guard rings by means of a precision voltage divider. The drift volume was bounded by the anode-cathode spacing of 6.44 cm and the 5.6 cm interior diameter of the guard ring. With this geometry and the measured variation of the glass encapsulated resistors ($\lesssim$ 1%), the calculated field deviates from the nominal or ideal value by < 3% out to 80% of the interior radius [12].

In order to maintain gas purity in this static cell, the system was of ultra-high vacuum construction and was periodically baked at $\sim 350^{\circ}$ for 48 hours to achieve and maintain low base pressures ($\sim 10^{-9}$ torr) and low outgassing rates (< 10^{-8}) torr/min). The gas samples (Airco) were procured

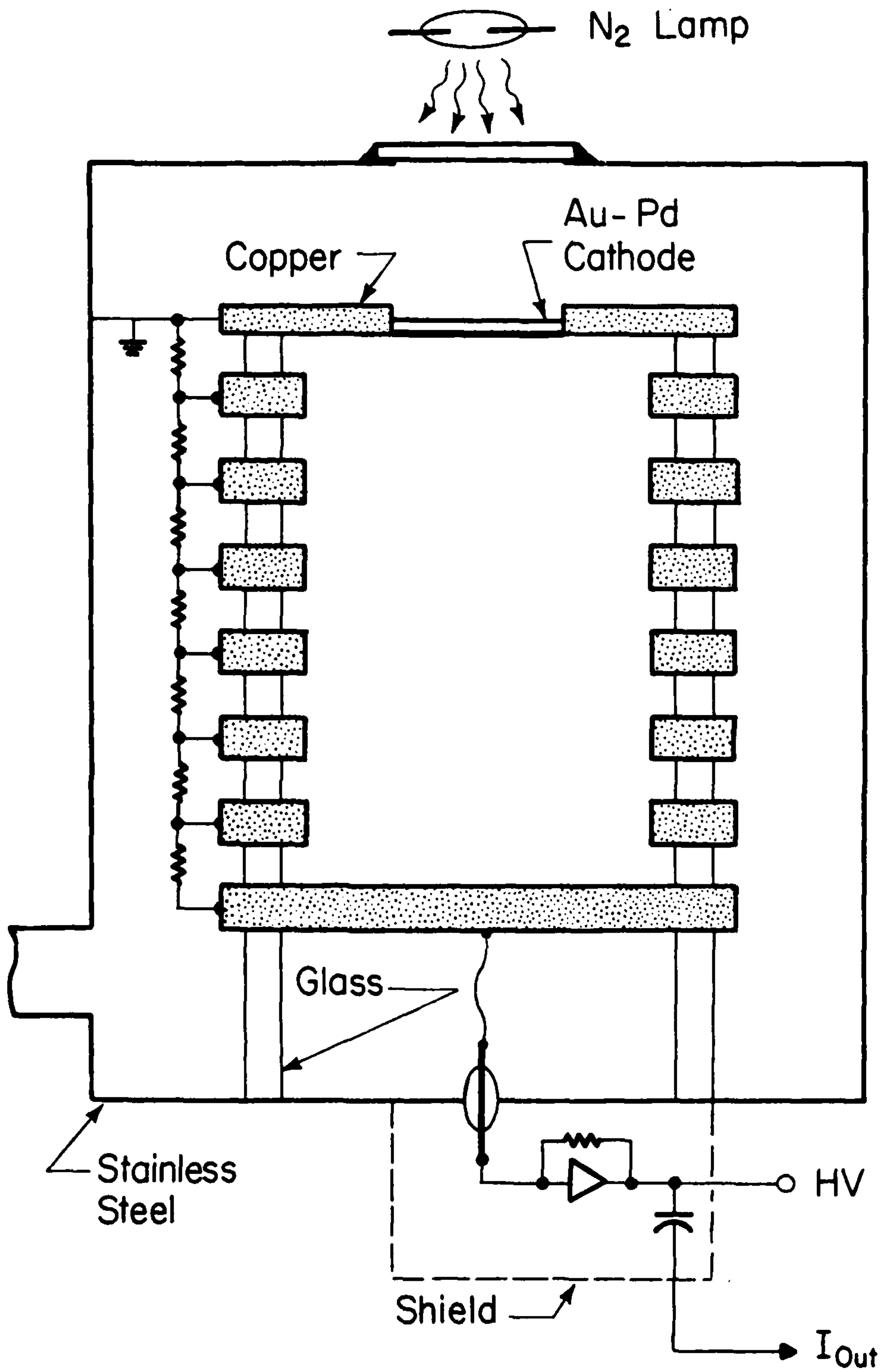

Fig. 3.1 Sketch of the swarm chamber. The guard rings are 5.6 cm ID, 8.6 cm OD and .9525 cm thick. The precision glass spaces are .159 cm thick. The glass encapsulated resistors are 100 M Ω, 1%. At the anode and cathode ends, the resistance and spacer thickness are half of the above values.

in glass bulbs of assayed research-grade quality with typical < 10 ppm impurity. Prior to filling, each gas was stored in a cold trap cooled with either liquid nitrogen or a pentane slush (~130°K) to remove any condensable impurities. Cell pressure was determined with a capacitive manometer and was typically in the range of 2 to 60 torr. The E/N ratio was determined to an estimated 5% accuracy, limited by the accuracy of the pressure measurements.

The quartz cathode, shown in Fig. 3.1, was 3 cm diameter and contained a 2 nm film of 40:60 Pd:Au alloy onto which a 3 nm film of Pd was deposited [13]. The electron pulse was produced by a small pulsed N_2 flashlamp (30 Hz, 2 μs FWHM) and the subsequent electron and ion currents were sensed with a fast (<.5 μsec), high impedance current-to-voltage converter (National Semiconductor LH0032C6) used in conjunction with a transient digitizer (Biomation 610B) and signal averager (Nicholet 1070). A typical current waveform consisted of a large electron contribution of ~ 10 μsec duration followed by a small ion contribution of ~.5 msec duration. To achieve an adequate signal to noise ratio, the electron portion was averaged over typically 4096 pulses. The ratio of the temporally integrated current contributions is then used to determine the ionization coefficient from, for example, one idealized relation $Q_{ion}/Q_{elec} = (1 - \exp(-\alpha^{+}L))$ where L is the drift distance.

In order to assure that the ionization coefficient was solely related to E/N, several diagnostic checks were initiated which included taking several measurements at fixed E/N but with various combinations of voltage and pressure, linearity checks by varying the intensity of the light source which showed that space charge effects were negligible for ion currents of < 200 pamps, outgassing checks over the time duration of a run (~ 6 hours) obtained by a comparison of the last data point with the first, and system checks with measurements on a known gas (N_2). During the above checks, no anomalies became evident.

Aside from normal errors, one possible source of error in these measurements is due to diffusion of the electron swarm to the guard rings. The size of the swarm region, which was dictated by practical constraints, involving geometry and signal levels was such that under worse case conditions, approximately 25% of the swarm could diffuse to the guard rings near

the anode. However, for weak ionization ($\alpha^{++}L \ll 1$) and small ion diffusion loss, there is no first order diffusion correction to the charge ratio Q_{ion}/Q_{elec}. More importantly, the carriers are drifting in a region of high field nonuniformity and may thus contribute with different ionization coefficients. Because these effects are somewhat difficult to quantify, then based on the size of the swarm and the high field region, we set an estimate of 25% as the worst case accuracy in these experiments even though the actual measurements appear somewhat better than this.

3.2.2 Results and Analysis

The results of the measurements are displayed in Figs. 3.2, 3.3 and 3.4 along with some previously measured values. Each data point represents an average of approximately 30 determinations with the error bars indicating the extrema in the values. There is substantial agreement between these data and earlier measurements in high E/N regions but at the lower E/N values, which were accessible in this experiment, but the measurements yielded values higher than might be anticipated suggesting other possible contributions. In what follows, we submit arguments that, because photoelectrons may be generated during the ion drift period by emission associated with the metastables, the overall measurements can be satisfactorily attributed to a sum of the true ionization rate (α^{+}/N) and a weighted metastable excitation rate ($f\alpha^{*}/N$), both of which are graphed in Figs. 3.2, 3.3 and 3.4 from a best fit determination.

We begin by noting that because of the experimental configuration and parameters, the avalanche multiplication is so small that the ideal result may be approximated by $1-x^{-\alpha^{+}L} \approxeq \alpha^{+}L$ with little error [14]. Hence if two contributions are present, we can set the experimentally measured coefficient to be $\alpha^{exp}/N = \alpha^{+}/N + \bar{\alpha}/N$ where $\bar{\alpha}$ is to be determined. Because of the smallness of the electron pulse, we can immediately ignore two-step and metastable-metastable ionization in this analysis and concentrate on metastable and ion contributions to $\bar{\alpha}/N$.

i. The γ processes. It is known that ion bombardment can cause the ejection of an electron which could be subsequently detected. Using the linearized multiplication, this would contribute a lowest order term $\bar{\alpha}/N = \gamma(\alpha^{+}L)\alpha^{+}/N$. Since $\alpha^{+}L\gamma \ll 1$, then the existence of the γ processes

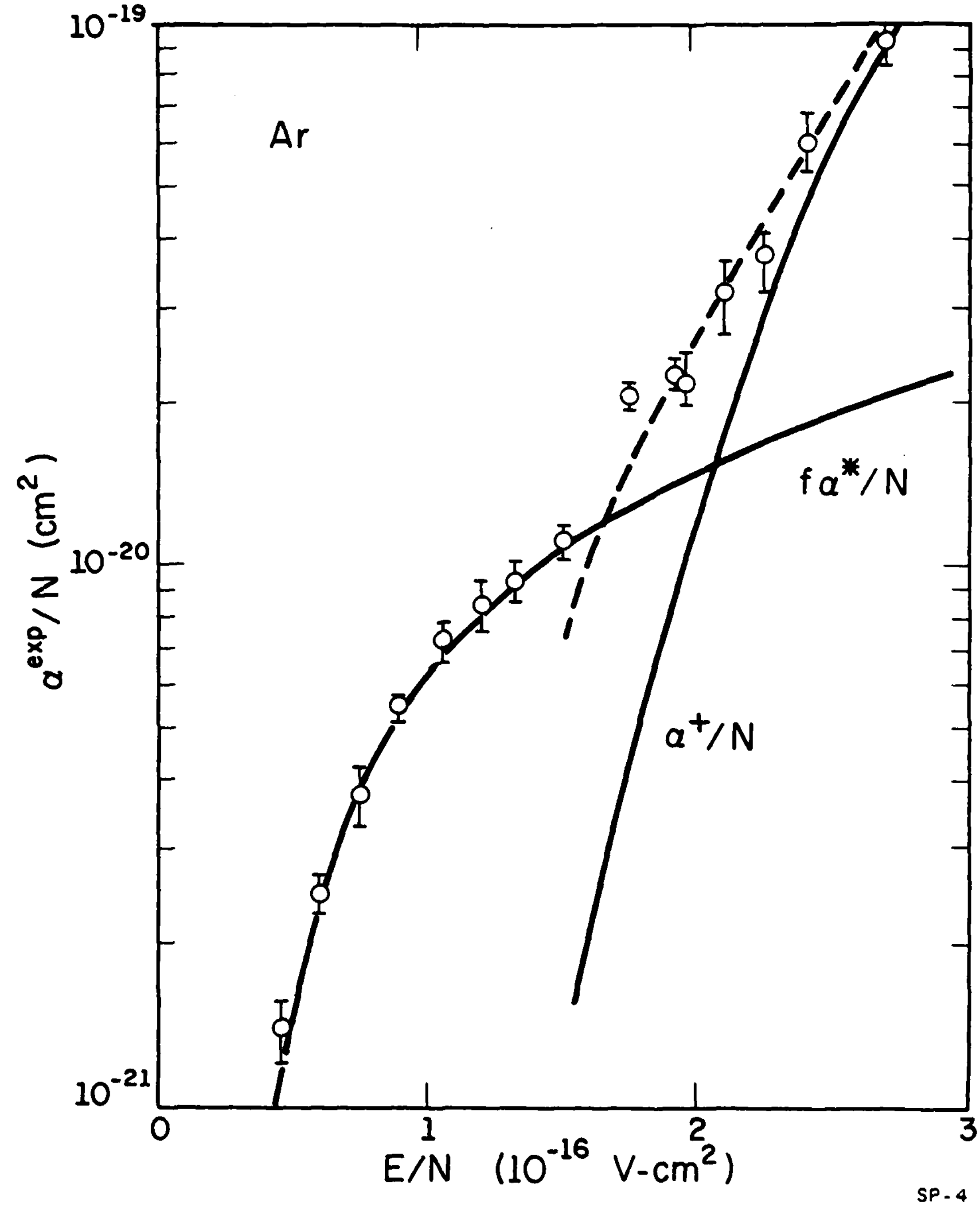

Fig. 3.2 Measured ionization coefficients vs. E/N for Argon at room temperature. The curves labelled α^+/N are from numerical calculations using an empirically determined value for f of 0.00074. The dashed line is from measurements in references 25 and 26.

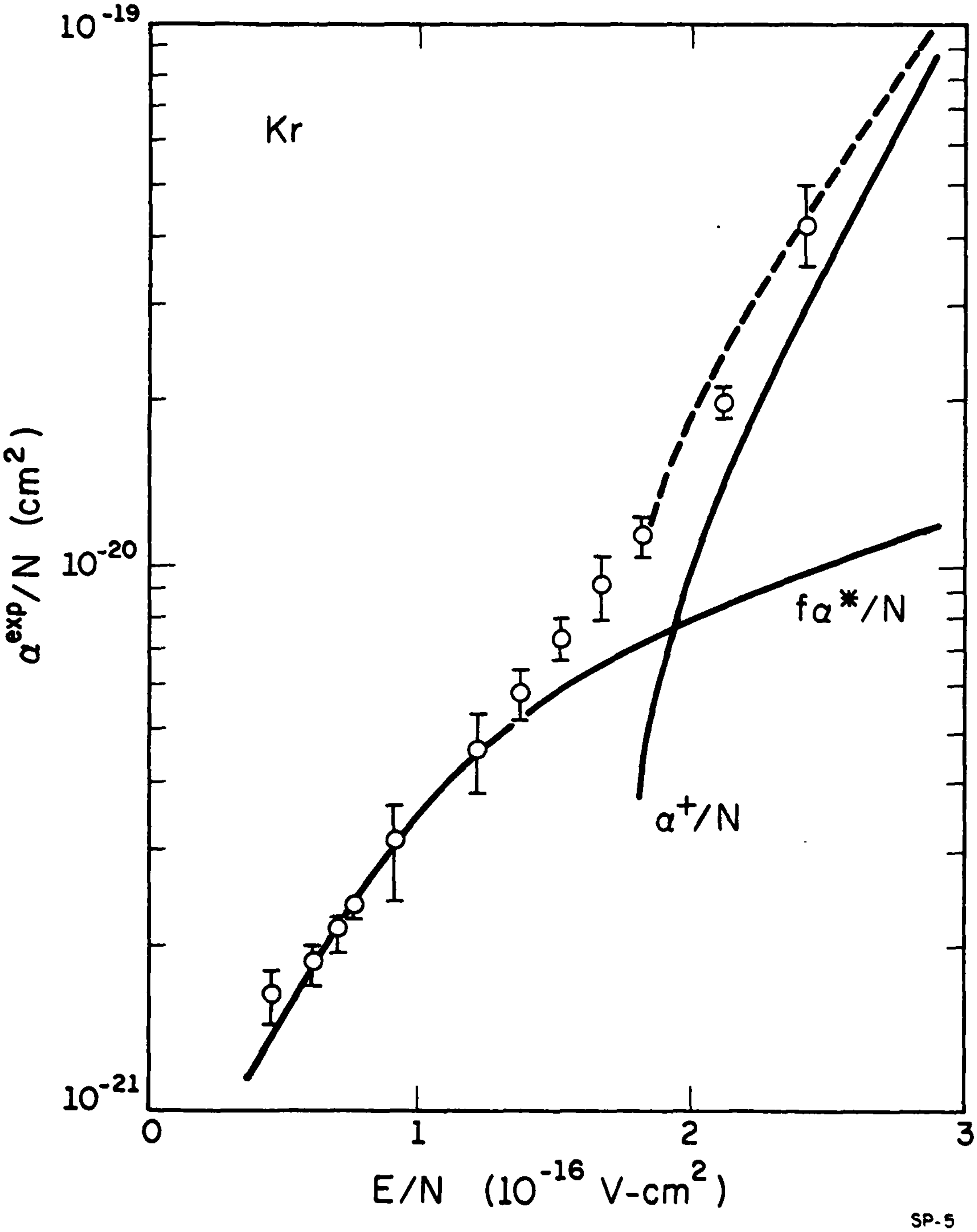

Fig. 3.3 Measured ionization coefficients vs. E/N for Krypton at room temperature. The curves labelled α^+/N and $f\alpha^*/N$ are from numerical calculations using an empirically determined value for f of 0.00042. The dashed line is from measurements in references 25 and 26.

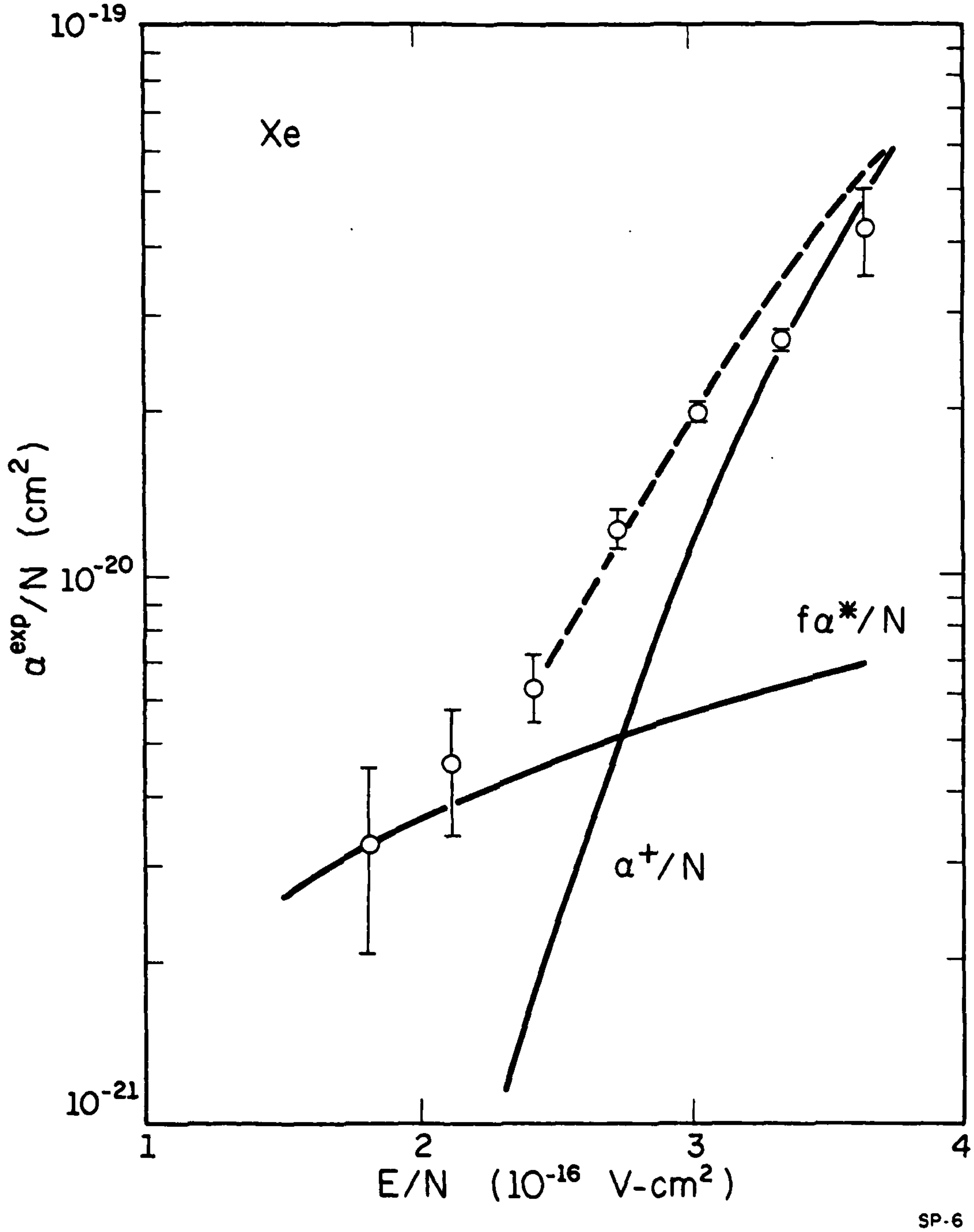

Fig. 3.4 Measured ionization coefficients vs. E/N for Xenon at room temperature. The curves labelled α^{+}/N and $f\alpha^{*}/N$ are from numerical calculations using an empirically determined value for f of 0.00016. The dashed line is from measurements in references 25 and 26.

would only perturb the results, and only tract α^{+}/N [15].

ii. Photoelectric emission. One characteristic of the rare gases is that the emission associated with the lowest excited states, either atomic or molecular, falls in the vacuum UV. Photoelectron emission from these would contribute as $\overline{\alpha}/N = f\alpha^{*}/N$, to first order, where f represents the fraction of the matastables which produce carriers and has an upper limit set by the photoelectric yield of the materials which is in the range $10^{-3}110^{-2}$ in this experiment [16]. More importantly, α^{*}/N is greater than α^{+}/N and has a different E/N dependence.

iii. Impurity effects. If impurities are present, photoionization, Penning ionization and direct electron impact ionization are possible. The concentrations for the first two can be estimated by using the empirical f values, gas kinetic rates and photoionization cross sections $\sim 10^{-17}$ cm^2. These yield concentrations of > 100 ppm for photoionization contributions and < 1 ppm for Penning contributions, both of which will be proportional to α^{*}/N, may exhibit pressure dependence, and require a low ionization potential impurity. Similarly, direct ionization contributions may require high concentrations, depending on the impurity properties, and, more significantly, would probably contribute with a functional dependence similar to the α^{*}/N curves in Figs. 3.2, 3.3, and 3.4. As a consequence of these estimates and the experimental procedures, impurity effects may, at most, contribute by Penning ionization, but the contribution is thought to be small due to the required low ionization potential and high vapor pressure at cryogenic temperatures. Hence, the dominant effect thought responsible for the observed behavior is photoelectron emission associated with excited metastables, probably with a strong molecular contribution due to the fact the formation time is $\lesssim$ 1 msec in these experiments.

As a test of this hypothesis, all exposed copper surfaces were subsequently coated with gold black which has approximately half the photoelectric yield of pure copper (and also a lower reflectivity) [16]. Measurements in Ar yielded α^{exp}/N values a factor of two smaller than shown in Figs. 3.2, 3.3, and 3.4 at low E/N (1.2×10^{-16}) and 25% smaller at high E/N (2.4×10^{-16}). For Ar, Kr and Xe, the empirical f value varied exponentially with metastable energy which is the characteristic yield behavior for low energy photoemission, again in support of the

hypothesis [17].

The experimental data was subsequently reduced by assuming two contributions as $\alpha^+/N + f\alpha^*/N$ using numerical solutions of the Boltzmann transport equation with the ionization cross section of Rapp and Englander-Golden and the momentum transfer cross sections of Frost and Phelps [18, 19,20]. The f value was empirically determined to yield the best fit between predictions and measurements. The available threshold inelastic cross sections include unnormalized beam-determined shape resonances and normalized cross sections from Eggarter and from Shaper and Scheibner [21,22,23]. The latter sets of cross sections did not yield good agreement but when the shape resonances were added and suitably normed, the resulting agreement was very satisfactory and is shown in Figs. 3.2, 3.3 and 3.4. The agreement with the higher E/N data measured by others and with drift velocity and characteristic energy data was also very good. The final set of cross sections are compiled in Table 3.1.

It is of interest to note that the major disagreement, using the various cross sections, occurred in the high E/N region, where direct ionization dominates, and not in the low E/N region [24]. Apparently α^*/N is sufficiently insensitive to the details of the cross section at these E/N values such that the α^+/N measurements still provide the most sensitive test data. In various tests, including using averaged values and using two state as opposed to single state losses, the resulting set of cross sections in Table 3.1 can only be claimed unique to about $\pm 20\%$, which is about the difference between the resonance peak and the average value.

3.2.3 Conclusions

We have measured the low field ionization coefficients in Ar, Kr and Xe and found that the experimental behavior could be attributed to two contributions, one associated with direct ionization and the other associated with metastables in the form of photoelectron emission. Since similar configurations were used in earlier measurements, it seems natural to invoke similar effects in order to account for the disagreement between calculations and measurements [24-27]. Using these data, a revised set of threshold inelastic cross sections was determined which differed from

Table 3.1 Threshold cross sections for Argon, Krypton and Xenon.

U(eV)	$\sigma(10^{-16}cm^2)$	U(eV)	$\sigma(10^{-16}cm^2)$	U(eV)	$\sigma(10^{-16}cm^2)$
11.50	0.0000	9.91	0.0000	8.32	0.0000
11.75	.0288	10.00	.0570	8.50	.0263
11.90	.0600	10.25	.0260	9.00	.1260
12.00	.0408	10.50	.0370	9.50	.1313
12.25	.0576	10.75	.0510	10.00	.1764
12.50	.0888	11.00	.0700	10.50	.2363
12.75	.1224	11.25	.0960	11.00	.4200
13.00	.1248	11.50	.1140	12.00	.8400
13.10	.1632	11.75	.1200	12.50	.8925
13.25	.1464	12.00	.1140	13.50	.9765
13.50	.1392	12.25	.1310	14.50	.9975
13.75	.1608	12.50	.1370	16.00	.9240
14.00	.1776	12.75	.1510		
14.25	.1920	13.00	.1710		
14.50	.2112	13.25	.2290		
14.70	.2280	13.50	.4000		
15.90	.3800	14.00	.7500		
16.50	.4800	15.00	1.0000		
17.50	.6100	18.00	1.5000		
18.50	.7500				
19.90	.9200				

previous ones primarily in the inclusion of shape resonances. Since α^+/N is manifestly more sensitive to the details of these cross sections than other transport data, there is still a need for low field data in order to further est and refine the cross section set. However, due to the metastable contributions identified in these experiments, it will be a challenge to construct an experiment for the determination of α^+/N which is immune to these effects.

3.2.4 Future Work

We are currently involved in the second state of this study, namely, exploration of the two- and three-body rate coefficients associated with the rare gas excited states. This work involves the use of a swarm for production of a high metastable density and subsequent selective excitation using a home built N_2-pumped dye laser. The time decay of the fluorescence is then monitored by a PMT connected to a Biomation 6500 transient recorder. To improve the signal-to-noise ratio, the output of the Biomation is then averaged over many laser pulses using a computer-based signal averager system. Progress in this area is well under way with the dye laser and signal averager system already operational. Future reports will be devoted to the results of this system.

3.3 Excitation Transfer Between Excited States in a Gas Discharge

3.3.1 Plasma Processes in Dry Processing

In recent years plasma etching using CF_4 discharge has become a topic of major interest. While studies have been made of the surface chemistry [28,29] and much has been inferred about the plasma kinetics, relatively little work has been done to directly characterize the plasma responsible for the production of the etching species. The work presented here is an initial report of an effort to study the processes occurring in the active volume of the plasma.

The experimental device used in the initial part of this study consists of a stainless steel cylindrical hollow cathode with an interior coaxial cylindrical wire basket anode. A discharge was initiated in CF_4 and spontaneous light emission was measured from one end of the cathode

through a quartz window. Since one of the roles of the 704 nm fluorescence from F^* suggested by the literature [30-33] is that of etch rate indicator, this relationship was performed in a variety of mixtures of Ar and CF_4 with a constant total pressure. The experiment was then repeated for He and CF_4.

The results, as shown in Fig. 3.5, yield the anticipated end points of a non-zero 704 nm emissions and a rapid etch in pure CF_4, and no 704 nm emission and no appreciable etch in pure Ar or He. In the x = 0.2 range, however, there is an appreciable increase in the magnitude of the 704 nm emission for the He-CF_4 mixes over the Ar-CF_4 mixtures, while etch rates are comparable. Note that the vertical scale for Fig. 3.5 had to be logarithmic to accommodate the large enhancement of the 704 nm line by helium. The large enhancement in a primarily helium discharge results from the pumping of the fluorine upper state by resonant transfer from the helium metastable.

$$He^* + CF_4 \rightarrow He + CF_3 + F^{**} \quad (1)$$

$$F^{**} \rightarrow F^* + h\nu \ (704 \text{ nm}) \quad (2)$$

$$F^* + (e, CF_4) \rightarrow F \quad (3)$$

Since the 704 nm transition is a well-known laser transition [34,35], it seems safe to assume that the lower state rapidly relaxes to the ground state (reaction 3) and thus the 704 nm line also serves as a monitor of the free fluorine production rate.

Thus Fig. 3.5 clearly shows that 704 nm emission is not an absolute indicator of the etching rate but merely a comparative indicator of the formation rate of free fluorine and its chemical fragment. Furthermore, the fact that the etch rate decreases even though the free fluorine rate increases in mixtures of helium and CF_4 indicates that the F, as well as its chemical fragment, is <u>not</u> the dominant participant in the surface reaction involved in the etching process. The same phenomenon can be found in an r-f discharge as is demonstrated in Fig. 3.6.

Here the 704 nm intensity versus CF_4 partial pressure was plotted for various power densities in a r-f induction discharge. For

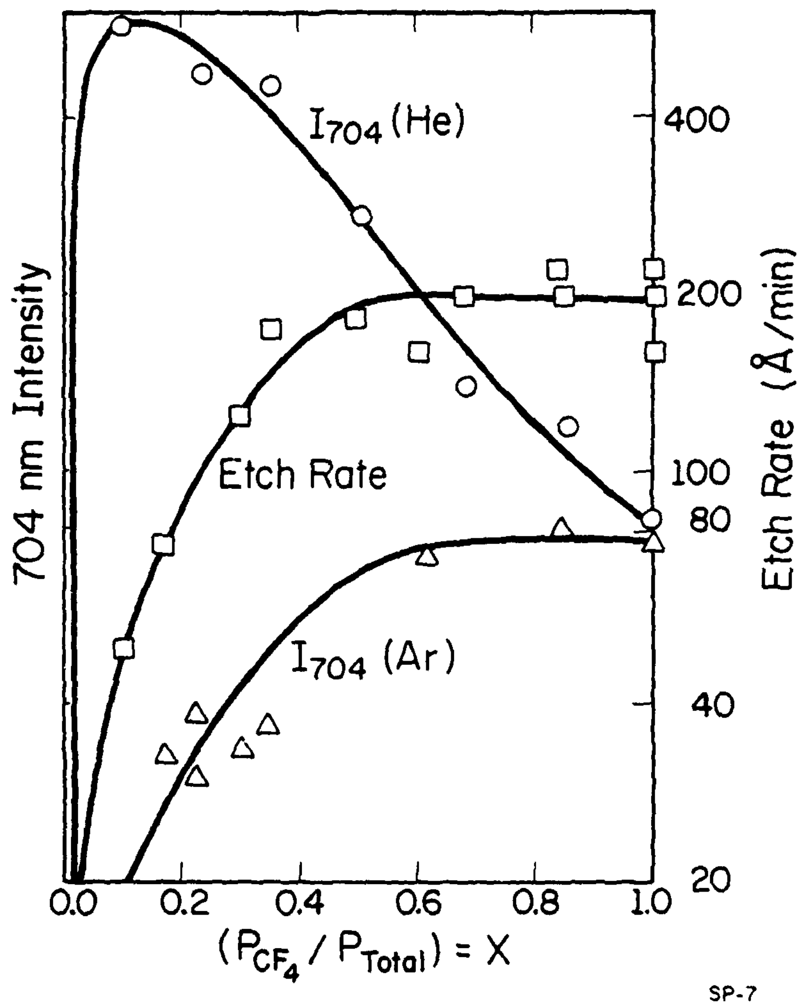

Fig. 3.5 Variation of etch rate and 704 nm spontaneous emission from free fluorine versus CF_4 partial pressure in He and Ar with a total pressure of 0.25 Torr. Note that the vertical scale is logarithmic.

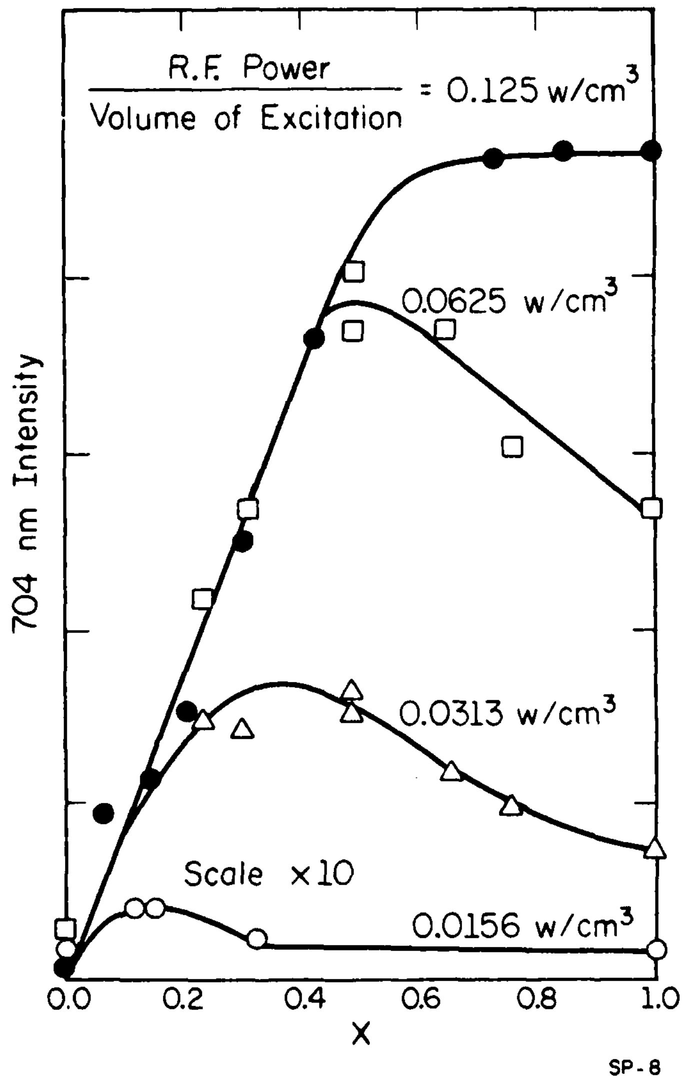

Fig. 3.6 Changing functional dependence of 704 nm emission for various power depositions in a r-f inductive discharge exhibits saturation behavior at high powers.

large power densities the 704 nm intensity exhibited a behavior similar to that of the etch rate but for low power densities it exhibited a behavior similar to that of the 704 nm intensity in Fig. 3.5.

Inasmuch as most published data have been taken on commercial etching machines - or reasonable facsimiles thereof - where etching rate is at a premium, it is most logical that second order processes play a major role. For instance, it is known that the helium metastable density responsible for reaction (1) will saturate with increasing current [36]. Hence, reaction (2), which is a consequence of (1) also saturates and is easily overwhelmed by other excitation channels, as is demonstrated in Fig. 3.6.

Thus, the above data does not negate the usefulness of the fluorine emission and free fluorine density to monitor the plasma excitation, but does serve as a caution light to attributing a direct causal relationship between these and the surface reaction (etching). Other spectroscopic features have been noted which do follow the etch rate in all cases and are the subject of further work.

Other work is also being undertaken to characterize the etching behavior in discharges with nitrogen trifluoride (NF_3) as the fluorine donor since it appears to etch about 40X that of the common CF_4 gas mixtures. We are currently attempting to understand the physics of this dramatically increased rate. (This work has resulted in the application for a patent for the use of NF_3 as an etchant.) Whether such an etchant will satisfy the practical requirements remains to be seen, but in any case, will provide a good test case for the understanding of discharges in these highly electronegative gases.

A more detailed account of the work outlined above has been submitted for publication in IEEE Transactions on Electron Devices. This information, along with some additional results, is the subject of an Abstract for a short talk to be submitted to the IEEE International Electron Devices meeting.

3.3.2 Basic Plasma Properties of Discharges in CF_4

The electron density in gas mixtures typical of those used in plasma etching discussed above, has been measured. This is a basic

parameter for all discharges and one that is potentially very important in the understanding of the mechanisms involved in plasma etching. The discharge configuration, pressure and current density were identical to those used in the actual etching experiments. The electron desnity was determined by the use of a double-pass microwave interferometer which indicated the change in phase shift of the wave passing through the plasma. This change is caused by the presence of the free electrons in the discharge which change the relative dielectric constant to $\epsilon_r \approxeq 1 - \omega_p^2/\omega^2$, $\omega_p^2 = N_e e^2/m \epsilon_o$, where N_e is the electron density, e the electronic charge, m the mass of an electron and ϵ_o the permitivity of free space.

The experiment was performed in mixtures of Ar + CF_4 and He + CF_4, as were the etching experiments. As Fig. 3.7 shows, densities in mixtures of Ar and CF_4 exhibit a well behaved variation with the partial pressure of CF_4. Such a variation is to be expected since the electron loss in these low pressure discharges is dominated by ion diffusion from the negative glow to cathode region and by electron attachment. To zeroth order, the ion diffusion does not change with the substitution of of CF_4 for Ar; however, the electron attachment is expected to be directly related to the density of CF_4. Hence, as Fig. 3.7 shows, the equilibrium density decreases with the partial pressure of CF_4.

However, the presence of Helium with CF_4 shows a much different behavior at first glance. The enhanced value of electron density is attributed to the Penning reaction

$$He(M) + CF_4 \rightarrow CF_3^+ + e + He \tag{4}$$

The spontaneous emission of the 704 nm excited fluorine line by reaction (1) was found to follow the product of the measured electron density and partial pressure of Helium - again indicative of the importance of reaction (1) of the previous subsection.

But, as has been noted there, the etch rate does not follow the spontaneous emission, but does scale directly with the electron density and the CF_4 partial pressure. Measurements similar to these will be made in NF_3. Furthermore, a microwave radiometer will be used to study the

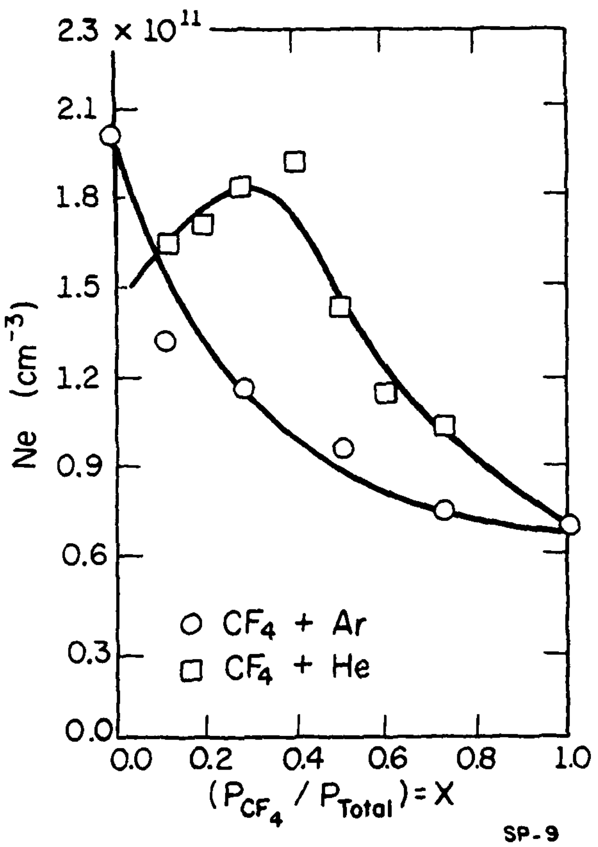

Fig. 3.7 Variation of the electron density in a discharge mixture of He and CF_4. p = 250 mTorr, cathode current = 0.5 ma/cm^2.

dependence of the radiation temperature of the gas mixtures.

A paper discussing these discharge measurements will be submitted to the Gaseous Electronics Conference.

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4.1 Introduction

This work involves basic studies of semiconductor materials properties, development of improvements in ion implantation and annealing, and applications to devices. Research on deep-level impurities and defects has been expanded to include deep-level transient spectroscopy (DLTS) measurements. In developing a DLTS capability for our research, we have extended existing methods to include improvements in data analysis and a new type of system amenable to studying junctions with significant leakage currents. The continuing study of ion-implanted compound semiconductors has been applied to the development of avalanche photodetectors in GaAs and InGaAsP. Considerable emphasis has been placed on both experimental and theoretical studies of basic semiconductor phenomena, including remote polar scattering near the $Si\text{-}SiO_2$ interface, effects of high fields on impurity scattering, and real-space transfer between layers in multilayer heterojunction devices.

4.2 Deep Level Transient Spectroscopy*

Deep Level Transient Spectroscopy (DLTS) [1] has become a widespread method for studying deep-level impurities and defects in semiconductors. Since several variations of the basic system are in use, we have evaluated various system effects and methods of data analysis which

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under Contracts DAAG-29-78-C-0016 and N00014-79-C-0424 and by the National Science Foundation under Grant DMR77-22228.

could affect the results obtained by different techniques. In the two most popular DLTS systems, one proposed by Lang [1] uses a dual channel boxcar averager for establishing a rate window, and another discussed by Kimerling [2] uses a lock-in amplifier instead. Either of these sampling methods requires certain assumptions which must be examined for reliable data reduction.

If a typical commercial capacitance meter is used to measure the transient capacitance, response time and overloading problems make it necessary to gate-off the signal for a certain initial period during the transient. For the boxcar averager case, it is possible to avoid problems arising from this gate-off requirement by setting the first sampling instant to occur after the gate-off period. For the lock-in amplifier case, however, this gate-off effect should be considered.

For the boxcar averager, measurement must be made using a non-zero gate width, instead of the infinitesimal sampling period originally assumed [1]. Therefore, a correct calculation of the thermal emission time constant must include this gate-width effect. When the lock-in amplifier is used, the phase adjustment is critical in addition to the gate-off effect. These effects can be included in the analysis and appropriate corrections can be made to account for them.

DLTS systems based on either a dual-channel boxcar integrator or a lock-in amplifier were analyzed for realistic experimental conditions [3]. We developed expressions which may be numerically solved to yield the DLTS rate window for cases of arbitrarily wide boxcar gates and for gating-off of the initial portion of the transient in the lock-in case. Solutions for typical experimental parameters show that the boxcar rate window may be adequately approximated by Lang's original expression applied to the midpoints of the gates. We find, however, that the lock-in DLTS systems are in general critically sensitive to the phase setting. We have analyzed in detail three possible modes of operation: (1) maximum signal, (2) phase referenced to the beginning of the truncated transient, and (3) phase referenced to the bias pulse. The first two methods show considerable shifts in the rate window relationship τ_{max}/T_o as a function of lock-in frequency when the initial portion of the transient is gated-off to avoid overload and recovery time effects. The third

method is much less frequency sensitive and thus is clearly the best choice for those who prefer lock-in operation. These concepts have been illustrated by DLTS measurements of the hole-emission spectra of the gold donor level in silicon n^+p diodes. The data show that a naive analysis of the first two modes of lock-in operation yields activation energies which are seriously in error. With proper analysis, however, the various DLTS methods produce identical results.

DLTS measurements require a capacitance bridge with high sensitivity and fast response to detect the usually small capacitance transient. Since diode leakage currents are highly temperature sensitive, a large leakage current always prohibits a bridge circuit from being balanced on a high sensitivity scale over a wide range of device temperatures. Naturally, it is desirable to keep the leakage current of the diodes as low as possible. However, applications of DLTS in the study of semiconductor defects often involve imperfect junctions. For example, diodes formed by ion implantation usually exhibit large leakage currents if the post-implant anneal conditions are not adequate to remove all radiation damage. As a consequence, it is difficult to apply DLTS to ion implanted structures, particularly in the study of partially annealed materials.

A new DLTS system [4] which allows measurement of leaky diodes is shown in the block diagram of Fig. 4.1. Two diodes having similar C-V and I-V characteristics are mounted on the same header to minimize the temperature difference between the two devices. The 20 MHz driving signals across these two diodes are set 180° out of phase by a phase shifter, and kept below 0.2 V peak-to-peak. Hence, the quiescent capacitances of the two diodes under the same reverse bias are well balanced at any temperature. As usual, we apply a periodic voltage pulse for trap filling and emptying to detect deep levels in the depleted region of the junction. In order to pulse the test diode only, the pulse must pass through two variable attenuators, a bandpass filter, and a power splitter before reaching the dummy diode. The power splitters are used for impedance matching and decoupling the interactions between the two output arms. Comparisons of results of this system with those of two standard systems show that the two-diode version is essential for accurate measurements on diodes exhibiting large leakage currents.

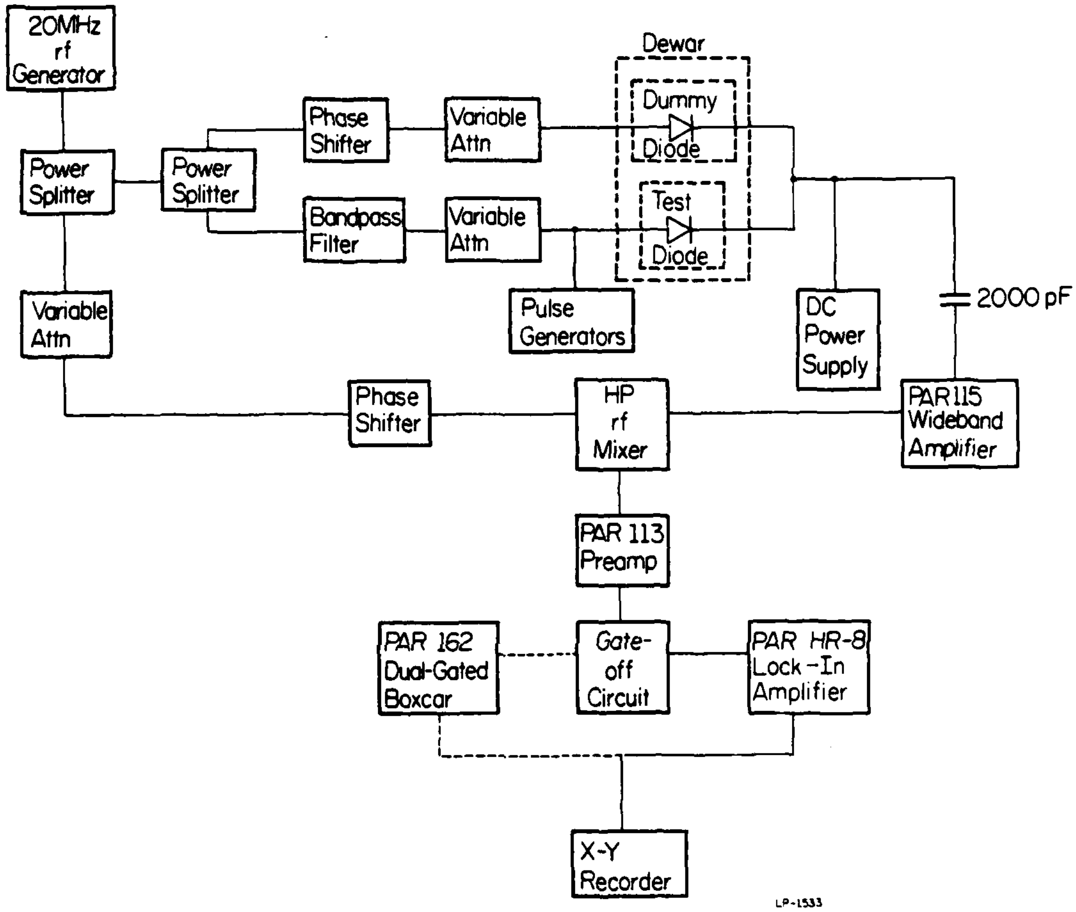

Fig. 4.1 Block diagram of a new DLTS system employing the two-diode method for measuring functions with significant leakage current.

4.3 Ion Implantation in Compound Semiconductors*

Studies of implantation, encapsulation, and annealing of III-V compounds has continued. We have examined the properties of Be-implanted junctions in GaAs, InP, and the InGaAsP system, and related these properties to implantation and annealing parameters. As an application of these methods, we have studied Be-implanted avalanche photodiodes in collaboration with G. E. Stillman.

GaAs p-n junction photodiodes [5] were fabricated by implanting Be ions at 250 keV to a dose of $10^{14} cm^{-2}$ into unintentionally doped n-type GaAs layers grown by VPE and LPE techniques on (100) oriented, n^+ substrates. These detectors are characterized by low leakage currents ($\lesssim$ 5 nA at 0.95 V_{br} for 250 μm diameter devices). The quantum efficiency at 8750 Å is 75% for devices with junction depths of 1.2 μm, p-type doping levels of 10^{18} cm^{-3}, and no intentional anti-reflection coating. Avalanche gains of 10-15 have been measured.

To extend the study of implanted junctions for optoelectronic devices, the effect of different annealing temperatures in the 450-800°C range on the photoluminescence of Be-implanted InGaAsP was examined. The results of these measurements indicate that the anneal temperature should be above 700°C for optimum Be activation. Avalanche photodetectors with leakage currents as low as 1 μA at 100 V and with gains $\gtrsim$ 100 at 116 V were fabricated using these implanted junctions. We find that the quantum efficiency for these devices is about 65% throughout the 1.00-1.30 μm wavelength range.

As a part of our continuing study of implantation and annealing of III-V compounds, we are examining the problems associated with the implantation of InP. In a portion of this work a scanning Auger microprobe (SAM) is employed to characterize the suitability of various dielectric films as encapsulants. In terms of mechanical properties and suppression of host atom outdiffusion, present data indicates that a P-doped silicon dioxide/Si_3N_4 dual layer structure is the most attractive. Another portion of this work employs a secondary-ion mass spectrometer (SIMS) for the

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determination of atomic Be profiles in InP as a function of annealing conditions. Preliminary results indicate that Be diffusion and redistribution during the anneal may be a more serious problem in InP than was the case in GaAs.

The electrical properties of Ge-implanted GaAs have been studied for a variety of implantation and annealing conditions (using rf plasma deposited Si_3N_4 as the encapsulant). We find that the implanted Ge exhibits a complex amphoteric behavior which is most likely defect controlled. With implantation temperatures of $100^{\circ}C$ and $200^{\circ}C$, n-type layers result for Ge doses ranging from 10^{13} to 10^{15} ions/cm^2 and annealing temperatures ranging from $750^{\circ}C$ to $850^{\circ}C$. With an implantation temperature of $-100^{\circ}C$, p-type layers are obtained instead for the same range of doses and annealing temperatures. For implants done at room temperature, n-type layers are obtained irrespective of the annealing temperature for doses of 10^{13}, 5×10^{14} and 10^{15} ions/cm^2. The intermediate doses of 5×10^{13} and 10^{14} ions/cm^2 result in p-type layers if the annealing temperature is no more than $800^{\circ}C$. The electrical activation and carrier mobilities are low in all cases. The carrier distribution profiles of room temperature implants are shallow ($\sim$900Å) and are characterized by a surface inactive layer. Photoluminescence spectra of these implants indicate that the annealing temperature for maximum lattice recovery is $850^{\circ}C$, but even at this temperature a great deal of residual damage still remains.

4.4 Transport Properties of Multilayer Heterojunction Structures*

Theoretical studies of scattering mechanisms in multilayer heterojunction structures have been performed. Our interest in this study was focused on conduction parallel to the heterojunction interface. Special attention has been paid to differences of the conduction mechanism in layered structures compared with bulk material. Three major effects turn out to be important in this connection:

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contracts DAAG-29-78-C-0016 and N00014-79-C-0424, and by the Office of Naval Research under Contract N00014-76-C-0806.

(1) The two-dimensional nature of the electron gas is significant in layers having a width typically below 200 Å. This gives rise to changes in the scattering probability. The primary result is an enhancement of plasmon scattering in these thin layers.

(2) The probability exists of confining scattering centers and charge carriers in different layers, giving rise to remote scattering.

(3) The step-like energy dependence of the scattering mechanism in multilayer structures can be exploited if the carriers leave the confined layers by thermionic emission to the neighboring layers. We propose a new class of devices based on this effect.

These three effects are discussed below, mainly for the case of Alternating GaAs-$Al_xGa_{1-x}As$ layers.

4.4.1 Confined Scattering

To calculate the electron-phonon scattering rate we start with the confined-particle (electron) wavefunction Ψ_{el} for n = 1 [7] and use the Frohlich Hamiltonian:

$$H_{el-ph} = \sum_{\vec{q}_{3d}} (C/q_{3d})(a_{\vec{q}_{3d}} e^{i\vec{q}_{3d}\vec{r}_{3d}} - a^{\dagger}_{\vec{q}_{3d}} e^{-i\vec{q}_{3d}\vec{r}_{3d}}). \tag{4-1}$$

The matrix element for phonon emission,

$$M = \left\langle \vec{k}', (N_q + 1) \middle| H_{el-ph} \middle| \vec{k}, N_q \right\rangle , \tag{4-2}$$

is then immediately obtained. $\vec{q}_{3d}$ is the three-dimensional phonon wave vector (q_x, q_y, q_z), and N_q the phonon occupation number. The other symbols have the usual meaning. The constant C is described below. Note that N_q more properly should be written as $N_{\vec{q}_{3d}}$ but for brevity has been simplified in Eq. 4-2. Integration of Eq. 4-2 over $\vec{r}$ yields

$$M = (-C/q_{3d})\, \delta_{\vec{k}-\vec{k}';\, \vec{q}} \sqrt{N_q + 1}\, B, \tag{4-3}$$

where $\vec{k}$, $\vec{k}'$ and $\vec{q}$ are two dimensional wave-vectors and

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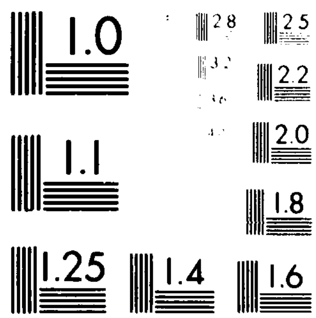

MICROCOPY RESOLUTION TEST CHART

$$B \equiv (2/L_z) \int_0^{L_z} e^{-iq_z z} \sin^2(\pi z/L_z)dz. \qquad (4\text{-}4)$$

Here L_z is the layer width. For $q_z L_z \lesssim 1$, $B \approx 1$ which is used below. The scattering rate for phonon emission is obtained from Fermi's Golden Rule and is

$$1/\tau_{em} = \{|C|^2 V/(4\pi^2\hbar)\} \int d\vec{q}\, dq_z (N_q + 1)\delta(E_{\vec{k}-\vec{q}} - E_{\vec{k}-\vec{q}} - E_{\vec{k}} + \hbar\omega_{LO})q_{3d}^{-2} \qquad (4\text{-}5)$$

The integration over q_z can easily be performed and gives

$$\int_{-\infty}^{\infty} dq_z/(q^2 + q_z^2) = (1/q) \int_{-\infty}^{\infty} dx/(1 + x^2) = \pi/q. \qquad (4\text{-}6)$$

Therefore we obtain

$$1/\tau_{em} = \{|C|^2 V/(4\pi\hbar)\}(N_q + 1) \int \delta(E_{\vec{k}-\vec{q}} - E_{\vec{k}} + \hbar\omega_{LO})dq d\phi. \qquad (4\text{-}7)$$

For polar optical bulk-phonons C is given by

$$C \equiv i\{2\pi e^2\hbar\omega_{LO}(\frac{1}{\epsilon_\infty} - \frac{1}{\epsilon_o})/V\}^{1/2} \qquad (4\text{-}8)$$

where ϵ_∞ and ϵ_o are the optical and static dielectric constants, e is the elementary charge, i represents the imaginary unit and V is the interaction volume. The comparison of the scattering rate given in Eq. 4-7 with the polar optical scattering rate in bulk GaAs shows that the scattering is enhanced in the layers. This is because the quantum well [7] provides momentum q_z. The enhancement depends of course on energy and is, on average, always smaller than a factor of 2.

A practical consequence of this confined scattering is e.g., that the threshold for Gunn oscillations is shifted to electric fields above 7 kV/cm in small ($L_z \lesssim 100$ Å) quantum wells.

4.4.2 Remote Scattering

In layered structures, the possibility exists that not only the electrons are confined but also the phonons. For example, the polar modes in GaAs-Ge layers are clearly confined to the GaAs. Nevertheless electrical fringing fields of the polar phonons couple to electrons in the nonpolar Ge. Therefore electrons (holes) can be scattered by polar interface materials. This effect is expected to be very important if the polar medium has a large coupling constant. This is the case for SiO_2, and we showed that the remote scattering mechanism is important in MOS-transistors, where it gives a major contribution to the energy loss. The theory is practically the same as that given before for the confined scattering case. Only $(\frac{1}{\epsilon_\infty} - \frac{1}{\epsilon_o})$ in the constant C has to be replaced by:

$$\frac{1}{\epsilon_\infty + \epsilon_n} - \frac{1}{\epsilon_o + \epsilon_n} \qquad (4\text{-}9)$$

where ϵ_n is the dielectric constant of the nonpolar medium.

Even more important than remote phonon scattering may be the possibility of remote impurity scattering. After the work of Esaki and Tsu [8], Dingle et al. [9] showed that the conduction electrons (going to the GaAs layer because of the lower conduction band edge) and their parent donors (in the $Al_xGa_{1-x}As$) can be separated via modulation doping of GaAs-$Al_xGa_{1-x}As$ layers, thereby reducing the influence of ionized and neutral impurity scattering on the electron motion in the GaAs. We have developed a theory for the remote impurity scattering which shows the following dependence of the scattering rate on the layer width L_z (assuming equal widths for the two types of layers):

$$1/\tau = \frac{e^4 m^* N_I^n}{16\pi h^3 (\epsilon\epsilon_o)^2 |\vec{k}|} \int_0^{2\pi} \frac{e^{-2|\vec{k}| L_z \sin\varphi/2} (1-\cos\varphi)}{(2|\vec{k}| \sin\frac{\varphi}{2} + S_1)^2 \sin\varphi/2} d\varphi \qquad (4\text{-}10)$$

Here N_I^n is the density of impurities in the $Al_xGa_{1-x}As$ layer and m^* is the effective mass. The geometrical configuration assumed for the calculation of Eq. 4-10 is shown in Fig. 4.2 where also an idealized picture of

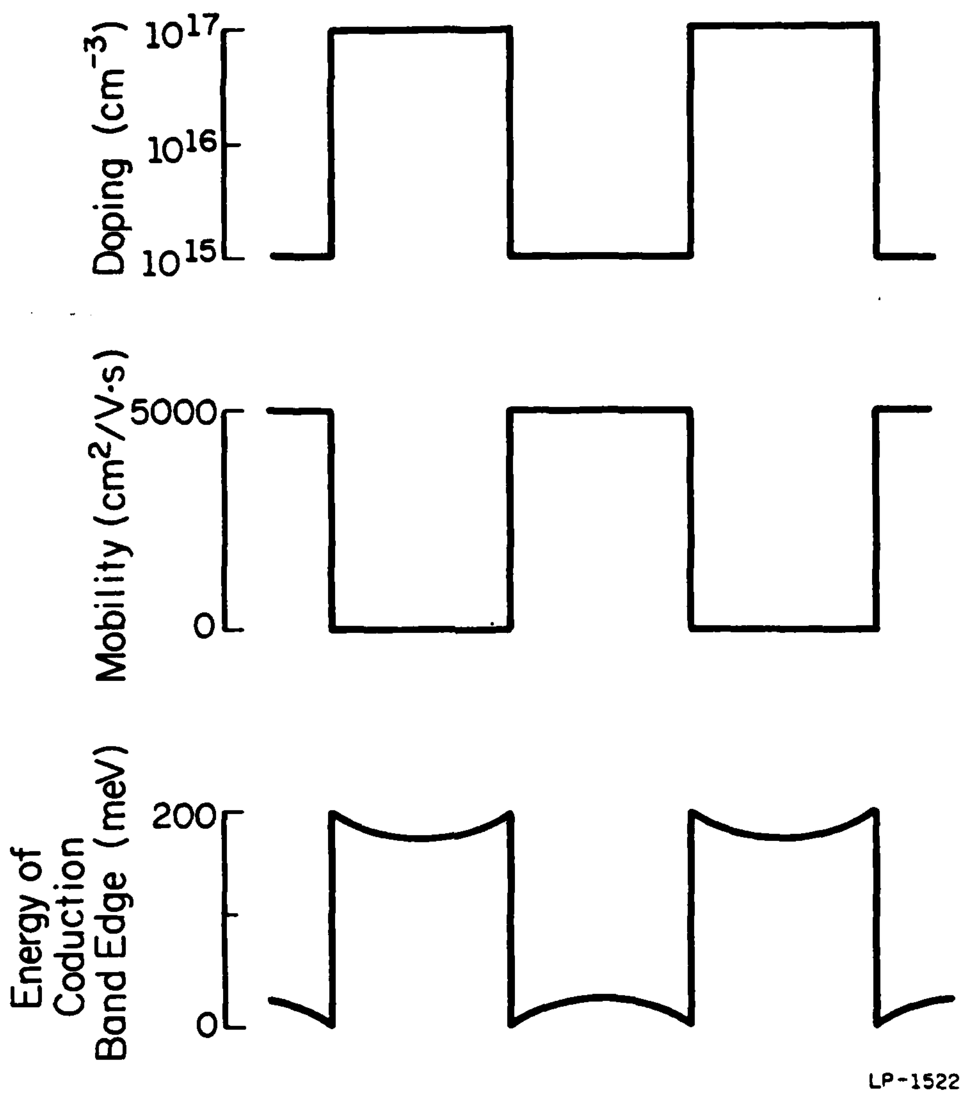

Fig. 4.2 Schematic sketch of band edge energies, electron mobility, and doping densities of modulation doped layers (continuum approximation).

mobility and doping profile is included. This situation, undoubtedly useful for a large number of applications, leads also directly to the step-like energy-dependent scattering and to a new class of devices which we propose below.

4.4.3 The Step-Like Energy-Dependent Scattering Rate and Real Space Transfer

Negative resistance effects in p-n junctions and bulk semiconductors have attracted much interest since the invention of the tunnel diode [10] and the Gunn diode [11]. The basic mechanism in Gunn devices is the transfer at high electric fields of electrons to conduction band valleys with high effective mass and corresponding low mobility. We propose a negative resistance device employing a different mechanism for electron transfer from a high-mobility state to a low mobility state. The basic structure of this device is a set of alternating GaAs and $Al_xGa_{1-x}As$ layers, or other lattice-matched materials with dissimilar band gap energies and electron mobilities. These multilayer structures may also employ modulation doping [9].

As described above, Fig. 4.2 shows the band structure of a set of modulation-doped layers and the doping distribution. Only the $Al_xGa_{1-x}As$ layers are doped in this case, and the electrons reside at minimum potential energy in the GaAs, where they experience strongly reduced impurity scattering, if they are separated from their "parent donors" by more than 200 Å. Thus for a layer thickness of typically 400 Å, the mobility, μ_1, in the GaAs layer will be high ($\gtrsim$ 5000 cm^2/V-s at room temperature) and the mobility, μ_2 of the charge carriers in the $Al_xGa_{1-x}As$ will be low (500 cm^2/V-s or less). Application of a low electric field parallel to the layer interface will result in current due primarily to electrons in the GaAs. A high electric field, however, will result in heating of the high mobility electrons to energies far above their thermal equilibrium value. Electron-electron collisions will help to randomize the energy gained in the field direction [11]. The low mobility carriers in the $Al_xGa_{1-x}As$ will not be heated significantly, since the power input per electron is equal to $e\mu_2F^2$, which is small. The power loss to phonons, however, is about the same in the two materials. As a

result, the electrons in the GaAs acquire a high kinetic energy and are able to reunite with their parent donors by diffusion and the electric field created by the donors. The transfer rate and the ratio of electrons residing in the GaAs to electrons in the $Al_xGa_{1-x}As$ are determined by the thermionic emission currents j_{1-2} from the GaAs to the $Al_xGa_{1-x}As$ and j_{2-1} going in the opposite direction. In the case of very high electron temperature [11] in the GaAs and about lattice temperature in the $Al_xGa_{1-x}As$ the Bethe theory (ref. 10, Chpt. 8) gives the result that almost 100% of the electrons will reside in the $Al_xGa_{1-x}As$ where the electrons have a very low mobility. We will return to that point below. During the transfer from the high mobility GaAs layer to the low mobility $Al_xGa_{1-x}As$ layer, the sample exhibits a negative differential resistance, as occurs in the Gunn effect. This device differs from the Gunn diode, however, in that the electrons leave the GaAs layer by thermionic emission and are transferred in real space to the $Al_xGa_{1-x}As$ layer where the mobility is low. The doping profiles, mobility, and band edge in Fig. 4.1 are plotted in the continuum approximation. There are, however, only three to four impurities on the average in the cross section of a 400 Å layer if the density of impurities is $10^{17}cm^{-3}$. Therefore instead of a smooth potential there will be potential fluctuations. This in turn broadens the mobility profile. Instead of a mobility step there will be statistical fluctuations and the mobility will decrease in a range of about 200 Å. The effect of this broadening on the device performance cannot be assessed with certainty at the present stage. Certainly the broadening decreases the peak to valley ratio. The broadening could be advantageous, however, for the device speed, since the electrons do not have to overcome everywhere the high potential barriers caused by their parent donors.

Preliminary calculations give the current-voltage characteristics of Fig. 4.3. We have also performed investigations of the switching speed of this negative differential resistance device. The result is that the switching time is of the same order as it is for the Gunn Effect, but it can be decreased by controlling the energy relaxation mechanism (phonon modes, confined and remote scattering, etc.). The main advantage of this real-space transfer mechanism over the usual k-space transfer devices should be higher peak to valley ratios achievable by strongly reducing

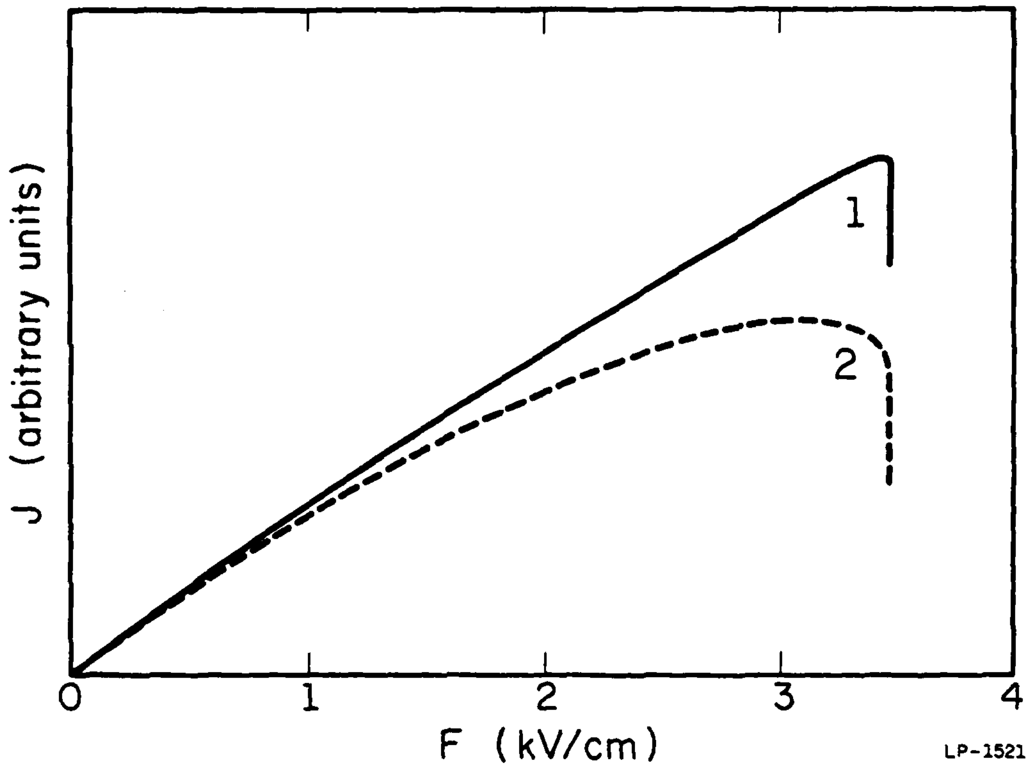

Fig. 4.3 Current voltage characteristic of an ideal real space transfer device. Curve 1 calculated for a conduction band separation of 200 meV and curve 2 for 100 meV. Note that the L minima in the GaAs are <u>above</u> the conduction band of the $Al_xGa_{1-x}As$ in these cases.

the mobility in the $Al_xGa_{1-x}As$ layers.

Having shown the possibility of a negative differential resistance by real-space electron transfer [12], we would like to point out that the basic mechanism of thermionic emission of hot electrons over such barriers allows for generalization and construction of other devices. For example, when the two types of layers are contacted so that the electrons can be heated in the layers separately, the electrons can be controllably shifted between the $Al_xGa_{1-x}As$ layers and the GaAs layers, which represents a memory effect.

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5. THIN FILM PHYSICS

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5.1 Introduction

The initial objective of this program was to investigate ion-surface interactions which have a controlling effect on the nucleation and growth kinetics, chemistry, and physical properties of alloy semiconducting films grown by sputtering. This objective has been broadened somewhat during the past year due to the surprisingly strong effects on elemental sticking probabilities, enhanced diffusion, and surface reactivity which we have observed during low energy ion bombardment of growing film surfaces. The nature of these effects makes them equally applicable to film growth by MBE (e.g. increasing the sticking probability of p-type dopants or decreasing the tendency toward surface segregation of many n-type dopants in GaAs) and reactive ion etching. Finally, these effects have been used to allow the growth of stable single crystal non-equilibrium structures such as $InSb_{1-x}Bi_x$ and $(GaSb)_{1-x}Ge_x$ alloys which have unusual properties and cannot be grown by other methods.

A review of the results obtained in the area of ion-surface interactions during the last year is contained in sections 5.2.1, 5.2.2, and 5.2.3 while detailed studies of the effects of these interactions on the growth and physical properties of single crystal GaSb and $InSb_{1-x}Bi_x$ films as well as polycrystalline InN are reviewed in sections 5.3.1, 5.3.2, and 5.3.3.

5.2 Ion-Surface Interactions

5.2.1 Ion Bombardment Enhanced Diffusion*

The first quantitative measurement of low energy (50-300 eV) ion bombardment enhanced diffusion [1,2] was reported in the 1977/1978 JSEP Progress Report. The effect is very large, resulting in diffusion coefficients as much as four orders of magnitude greater than thermal values in III-V compounds. This is important not only for controlling the composition distribution in sputtered alloy films and the abruptness of heterojunction interfaces, but also in MBE films grown using accelerated dopant beams. Furthermore, such enhanced diffusion effects must be accounted for in determining altered layer thicknesses due to preferential sputtering of alloy targets and deconvoluting compositional depth profiles obtained by surface analytical techniques such as AES and SIMS.

Experimental techniques, described in detail in references 1 and 2 were established for direct measurement of enhanced diffusion coefficients, D^*, over very short distances ($\lesssim$ 60 Å). For this work, a series of superlattice structures, each with equilayer thicknesses between 10 and 30 Å, were grown by multi-target rf sputtering under varying degrees of ion bombardments. (Film growth results were discussed in reference 2). Standing wave X-ray diffraction analysis was then used to measure the period and amplitude of the composition modulation wave as a function of glow discharge ion bombardment conditions during film growth. These results were then related directly to D^* through a simple analytical model discussed in references 1 and 2. As an example, for InSb/GaSb interdiffusion, D^* was found to be 1.1×10^{-17} cm^2/sec for Ar bombardment in a 15 mTorr plasma compared to a thermal value of $<10^{-22}$ cm^2/sec. Experiments carried out in a UHV multiple ion beam system (constructed under JSEP sponsorship) in which the ion energy, flux, and impingement angle can be carefully controlled are presently underway.

A second, although experimentally much more difficult, technique for the direct measurement of low energy ion enhanced diffusion bombard-

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*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contracts DAAG-29-78-C-0016 and N00014-79-C-0424.

ment has also been developed. In this technique, a supersaturated single phase alloy is electrochemically thinned until it is electron transparent (i.e. $\lesssim$ 2000 Å) over an area of several mm^2. The sample is then examined in a scanning transmission electron microscope (STEM) in order to characterize it metallurgically as well as to establish that it is still single phase. Following this step the sample is bombarded with low energy ions of a given energy at a given dose and examined again in the STEM. This procedure is continued until a sufficiently high dose is reached to promote ion bombardment induced second phase precipitation over the affected region. Knowing the concentration of the randomly distributed solute in the supersaturated alloy and measuring the average precipitate size and number density allows a depth-averaged enhanced diffusion coefficient to be determined. The nature of the second phase precipitates can be established unambiguously using light field-dark field microdiffraction techniques and the thickness and depth of the precipitates can be estimated using a tilt stage.

5.2.2 Effect of Ion Bombardment on Elemental Sticking Probabilities During Film Growth*

We have recently shown [3] that low energy ion bombardment during film growth can play a large role in controlling elemental sticking probabilities and allowing an extension in the growth temperature range over which stoichiometric III-V compounds and alloys are formed as well as allowing the growth of non-equilibrium phases (see section 5.3.2). Figure 5.1 shows the relative incorporation probability of Sb into GaSb and InSb films grown on (100) GaAs substrates as a function of the growth temperature, T_s, and the ratio, r, of the Sb to Ga (or In) elemental impingement rates at the growing film. Data points were obtained using both III-V and $III_{0.3}V_{0.7}$ targets. σ_{Sb} is defined as

$$\sigma_{Sb} = C_{Sb}/rC_{III} \qquad (5.1)$$

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contracts DAAG-29-27-C-0016 and N00014-79-C-0424.

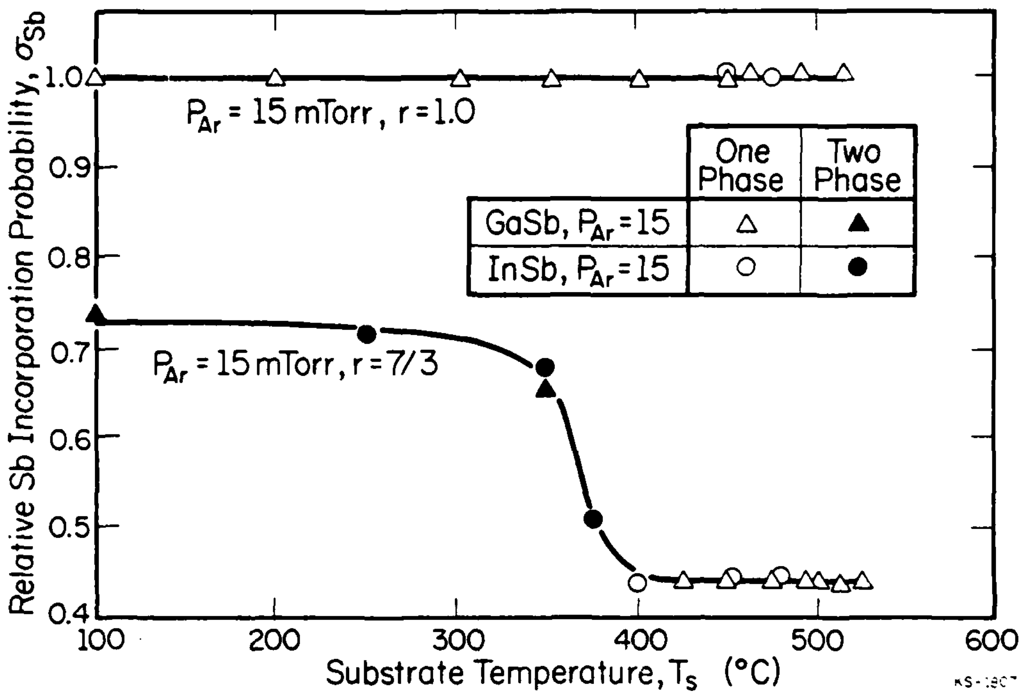

Fig. 5.1 The relative Sb incorporation probability in sputter-deposited GaSb and InSb films as a function of film growth temperature and Sb to Ga (or In) incident flux ratio.

where C_{Sb} and C_{III} are the measured concentrations of Sb and Ga (or In) in the film. The relative incorporation probability defined in this way combines the elemental thermodynamic sticking probability φ with the net excess resputtering probability Γ of Sb during film growth. For films grown from a stoichiometric target, σ_{Sb} was found to be unity up to the highest T_s values investigated, $510^{o}C$. For comparison, InSb films grown by flash evaporation from stoichiometric source material have been reported to contain second phase In precipitates for growth temperatures above $460^{o}C$ [4].

Films sputter deposited from the $III_{0.3}V_{0.7}$ targets at 15 mTorr Ar were found to be stoichiometric for $T_s > 400^{o}C$ (i.e., $\sigma_{Sb} = 1/r = 3/7$), but σ_{Sb} increased rapidly below this temperature. The transition region was rather sharp with σ_{Sb} becoming constant at ~ 0.74 (i.e. film composition $\sim III_{0.37}V_{0.63}$) for $T_s < 350^{o}C$. Evaporated films grown at similar values of r also exhibited a transition region in the same T_s range above which the films were stoichiometric. However, below the transition temperature region $\sigma_{Sb} = \varphi_{Sb} \equiv 1$ for evaporated films which are two-phase containing Sb precipitates. Thus in the present experiments, σ_{Sb} in sputtered GaSb and InSb films grown at T_s less than the transition temperature has been reduced by approximately 26% over that observed in evaporated films. This reduction in σ_{Sb} is due to the induced negative substrate bias as discussed below.

The effect of an applied negative substrate bias, V_s, on film composition is shown in Fig. 5.2. In these experiments the films were grown from $Ga_{0.3}Sb_{0.7}$ and $In_{0.3}Sb_{0.7}$ targets at $T_s \leq 250^{o}C$. Increasing V_s resulted in a monotonic decrease in σ_{Sb} until stoichiometry was achieved for V_s values larger than approximately-75 V. No evidence for preferential resputtering from stoichiometric films was obtained for V_s values up to 250 V. The decrease in σ_{Sb} with V_s was not a thermal effect. The increase in T_s with substrate bias, even for the highest value of V_s used, was less than $75^{o}C$, which can be seen from Figs. 5.1 and 5.2 to have no effect on the results. From the slope of the σ_{Sb} vs. V_s curve, one can extrapolate σ_{Sb} to 1 (i.e., a film composition of $III_{0.3}V_{0.7}$) and estimate an induced substrate bias of approximately -75 V with respect to the positive space charge region in the plasma for the 15 mTorr results shown in Fig. 5.1.

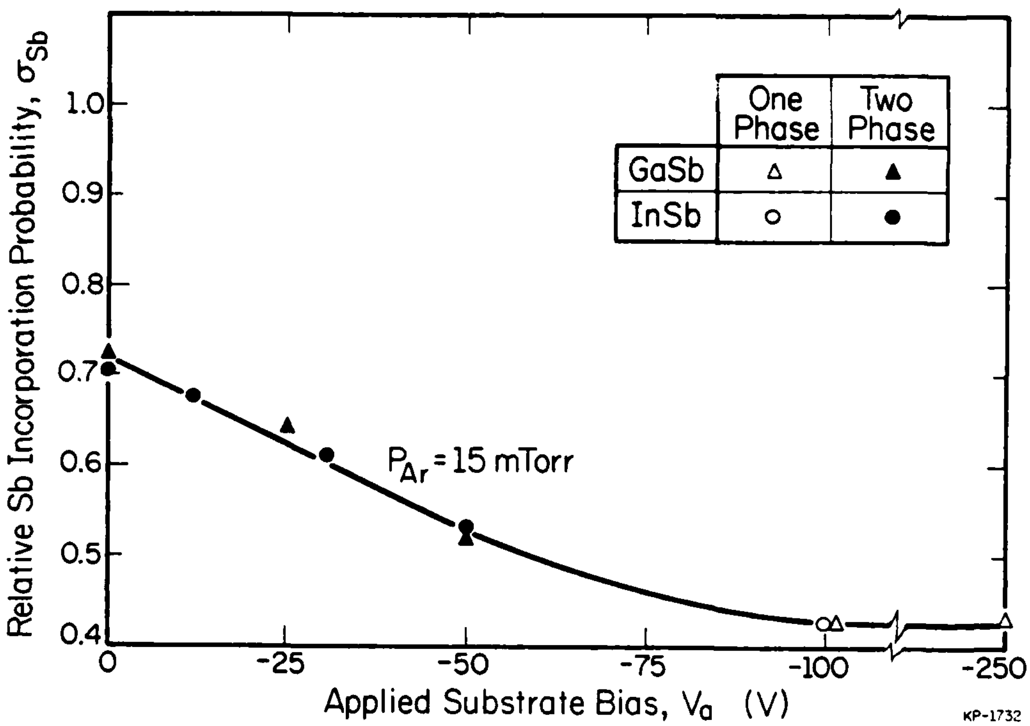

Fig. 5.2 The relative Sb incorporation probability in sputter-deposited GaSb and InSb films as a function of applied substrate bias.

These results show that the range of r at a given T_s over which stoichiometric GaSb and InSb films grown from the vapor phase may be obtained can be extended to larger values by applying a negative substrate bias during growth. r can also be extended to values less than one as demonstrated by a series of film growth experiments using a two-phase In + InSb target. The application of a substrate bias during film growth was found to decrease the excess In concentration in the film and for any set of growth conditions used, a critical bias could be found such that for applied substrate biases greater than this value, the films were stoichiometric.

From Fig. 5.2 it is clear that for the range of applied negative substrate biases used in these experiments, 0-250 V, no preferential resputtering from stoichiometric films was obtained during deposition. Thus, in the case shown in Fig. 5.1 for film growth from stoichiometric targets under conditions in which the induced negative substrate bias was on the order of 75 V, the deposited films were stoichiometric even for the highest growth temperature investigated, 510°C. For InSb, this exceeded the growth temperature limit observed for evaporation starting from stoichiometric source material [4]indicating that excess In in the sputtered films, resulting from the reduced thermal sticking probability of Sb on InSb at $T_s \geq 460°C$, was being resputtered.

The curve in Fig. 5.1 corresponding to the case in which $r = 7/3$ indicated preferential resputtering of excess Sb occurs at T_s values below the transition region. The observed temperature range of the transition region was the same for both GaSb and InSb since it was controlled by the equilibrium vapor pressure of Sb over metallic Sb, P_{Sb}^{Sb}. Thus, for either GaSb or InSb, Sb begins to precipitate out at growth temperatures below that which corresponds to P_{Sb}^{Sb} being equal to the partial pressure of Sb in the discharge. As Sb begins to precipitate, preferential resputtering occurs forcing the σ_{Sb} vs. T_s curve to turn over at an σ_{Sb} value less than one. σ_{Sb} attains a constant value at the growth temperature for which $\varphi_{Sb} \rightarrow 1$ and for all lower growth temperatures remains at a value given by

$$\sigma_{Sb} = \frac{1}{r}\,\frac{J_{Sb}\varphi_{Sb} - R_{Sb}}{J_{III}\varphi_{III} - R_{III}}$$

where J and R are impingement and resputtering rates, respectively, and φ_{III} is approximately one over the range of T_s investigated. The results in Figs. 5.1 and 5.2 show that for cases in which $J_{Sb}\varphi_{Sb} = J_{III}\varphi_{III}$, $R_{Sb} = R_{III}$ and no preferential resputtering occurs. On the other hand, when $J_{Sb}\varphi_{Sb}$ is either larger or smaller than $J_{III}\varphi_{III}$, preferential resputtering occurs in a direction such that second-phase precipitation is either minimized or eliminated depending on the magnitude of V_s.

According to Sigmund's sputtering theory [5], elemental resputtering yields are proportional to a term which expresses the efficiency of momentum transfer in the collisionally excited region of the lattice divided by the surface binding energy of the species in question. For purposes of sputtering yield calculations, elemental surface binding energies are approximated by their heat of sublimation, ΔH^{s}_{298}, which for Sb is 62.6 kcal/mol. The equivalent quantity for a compound would be the heat of formation from the gas phase ΔH^{fg}_{298} which is obtained by adding the normal heat of formation of the compound to the sum of the heats of sublimation of the constituents. This gives 265.3 and 246.2 kcal/mol for GaSb and InSb, respectively. For nearly-stoichiometric films, the actual binding energy of Sb in the nucleating precipitates is something between ΔH^{s}_{298}(Sb) and ΔH^{fg}_{298}(compound) since the precipitates are not fully developed and a given Sb atom in a nucleus is more realistically envisioned as bonded to Sb-rich GaSb (or InSb). Nevertheless, it is clear that the sputtering probability from such nuclei is larger than that of Sb in the compound matrix and a small negative bias potential applied to the substrate during film growth enlarges the range of T_s and r over which stoichiometric films may be obtained. This allows the use of very high r values during MTS film deposition resulting in the growth of GaSb single-crystal films with some of the lowest reported room temperature carrier concentrations at $p \simeq 5 \times 10^{15} cm^{-3}$ (see section 5.3.1).

5.2.3 Ion Bombardment Induced Surface Reactions: Reactive Ion Etching*

A new program designed to investigate fundamental mechanisms of processes occurring in the plasma as well as at the plasma-surface interface which control the reactive ion etching of Si, SiO_2, and Si_3N_4 has been initiated. In this work we will use optical probing techniques such as Glow Discharge Optical Spectroscopy [6-10] and Glow Discharge Absorption Spectroscopy [11], which were developed in this laboratory under JSEP sponsorship, to investigate plasma processes and UHV surface analytical techniques such as AES and XPS to investigate ion bombardment catalyzed surface reactions under well controlled conditions. We believe that a basic understanding of both the plasma chemistry and the surface chemistry under controlled conditions must first be obtained before the overall process under commercial etching conditions can be understood.

In preliminary experiments using CF_4, CF_4 + Ar, and $CF_4 + O_2$ plasmas with Si and Al targets we have categorized atomic emission lines and molecular bands in the spectral range from 2500 Å to ~8000 Å. Several new and important peaks such as the bands due to SiF and the C atomic lines, which have not been previously reported during CF_4 etching of Si, have been discovered. The change in intensity of these as well as other peaks due to Si, F, F_2, CO, CO_2, O_2, etc. with etching conditions are extremely useful in sorting out important plasma reactions. For a given set of experimental conditions, we also observe large changes in peak intensities in different plasma regions providing information on electron temperatures and molecular association and dissociation reactions. Quantitative analysis using specially designed absorption cells is just beginning.

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*This work was supported by IBM Research Laboratories, East Fishkill, New York.

5.3 Crystal Growth

5.3.1 GaSb*

Single-crystal GaSb films have been grown on semi-insulating (100) GaAs substrates using multitarget sputtering to vary the Sb/Ga atomic flux ratio r impinging on the growing film [12,13]. The effects of systematic variations in growth variables (r, growth temperature, target voltage, and Ar sputtering gas pressure and purity) on the electrical properties of deposited films was evaluated. Temperature-dependent (8-600°K) Hall coefficient and resistivity measurements were carried out on all films in order to determine the concentration and ionization energies of impurity and point-defect levels. In all cases the Hall-coefficient measurements could be fitted with two acceptor levels and a net concentration of very shallow (<1 meV) acceptors.

Analytical expressions were used to fit Hall coefficient data over the measurement range 8-600°K. Such fittings allowed a determination of the concentrations N_j and ionization energies E_j of the dominant trap levels and the ratios of the electron-to-hole mobilities b. In deriving the analytical expressions, a three-band (one conduction and two valence bands) approximation was used.

The Hall coefficient measurements for all films could be fitted with two acceptor levels of concentration N_{A1} and N_{A2} at ionization energies of 40 and 80 meV, respectively, above the valence-band edge. A net ionized acceptor concentration, $N_A - N_D$, with an ionization energy less than 1 meV was also obtained. The origins of these levels were investigated by following the changes in their concentrations with film growth parameters including substrate temperature, excess-Sb flux, target voltage, sputtering pressure, and sputtering gas purity. N_{A1} ranged from 6×10^{15} to $3 \times 10^{17} cm^{-3}$, N_{A2} from 5×10^{15} to $1 \times 10^{17} cm^{-3}$, and $N_A - N_D$ from 6×10^{15} to $6 \times 10^{17} cm^{-3}$ All the observed changes with growth parameters could be accounted for by assuming that the levels $N_A - N_D$ and N_{A1} were related to Sb vacancies or equivalent nonstoichiometric point defects, that $N_A - N_D$ was also sensitive to ionized oxygen donors, and that N_{A2} was related to charged active sites on dislocation lines.

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contracts DAAG-29-27-C-0016 and N00014-79-C-0424.

The increase in both $N_A - N_D$ and N_{A1} with T_s as shown in Figs. 5.3 and 5.4 was the result of a corresponding decrease in the Sb sticking probability. At a given T_s value, the concentrations of both levels were less for films grown from the $Ga_{0.3}Sb_{0.7}$ target than for those grown from the GaSb target and the lower the T_s value, the larger was the difference in level concentration between the two sets of films. Furthermore, $N_A - N_D$ as well as N_{A1} exhibited a rapid decrease with increasing excess-Sb flux as shown in Figs. 5.5 and 5.6. The rate of decrease of both concentrations was again higher at lower T_s values. Thus, irrespective of the targets used, increases in excess Sb flux or Sb sticking probability led to proportional decreases in both $N_A - N_D$ and N_{A1}.

Bulk GaSb grown from solution using high-purity elements has consistently been found to contain acceptor concentrations on the order of $1 \times 10^{17} cm^{-3}$ [14,15]. Further zone refining as well as variations in crystal growth technique and crucible materials [16] resulted in essentially no reduction in the hole density. The presence of "usual" chemical impurities was excluded by spectrographic analysis [17]. Some reduction in the carrier concentration was achieved by growth from Sb-rich melts [18,19]. This indicated that the residual acceptor might be caused by nonstoichiometric Sb-deficient or Ga-rich lattice defects and $V_{Ga}Ga_{Sb}$ centers were suggested. However, a possible change in the segregation coefficient of other impurities as a function of Sb content in the liquid could not be entirely ruled out. In the present investigation, the change in the relative amount of Sb incorporated in GaSb films was affected by independent variations in both the incident Sb/Ga flux ratio using two different excess-Sb target combinations and the Sb sticking probability through variations in the substrate temperature. Therefore, this work strongly supports nonstoichiometric Sb-deficient point defects as the origin of the inherent acceptors.

The slope of the N_{A1}-vs.-r curve shown in Fig. 5.6 allows an estimate of the width of the compound phase field in GaSb. Assuming that the number of excess Sb vacancies per electrically active defect center is a small integer, in this case 1, and combining this with the limiting value of r at which metallic Sb is precipitated as observed by x-ray diffraction, the widths of the phase field at 450 and 500^{o}C are calculated

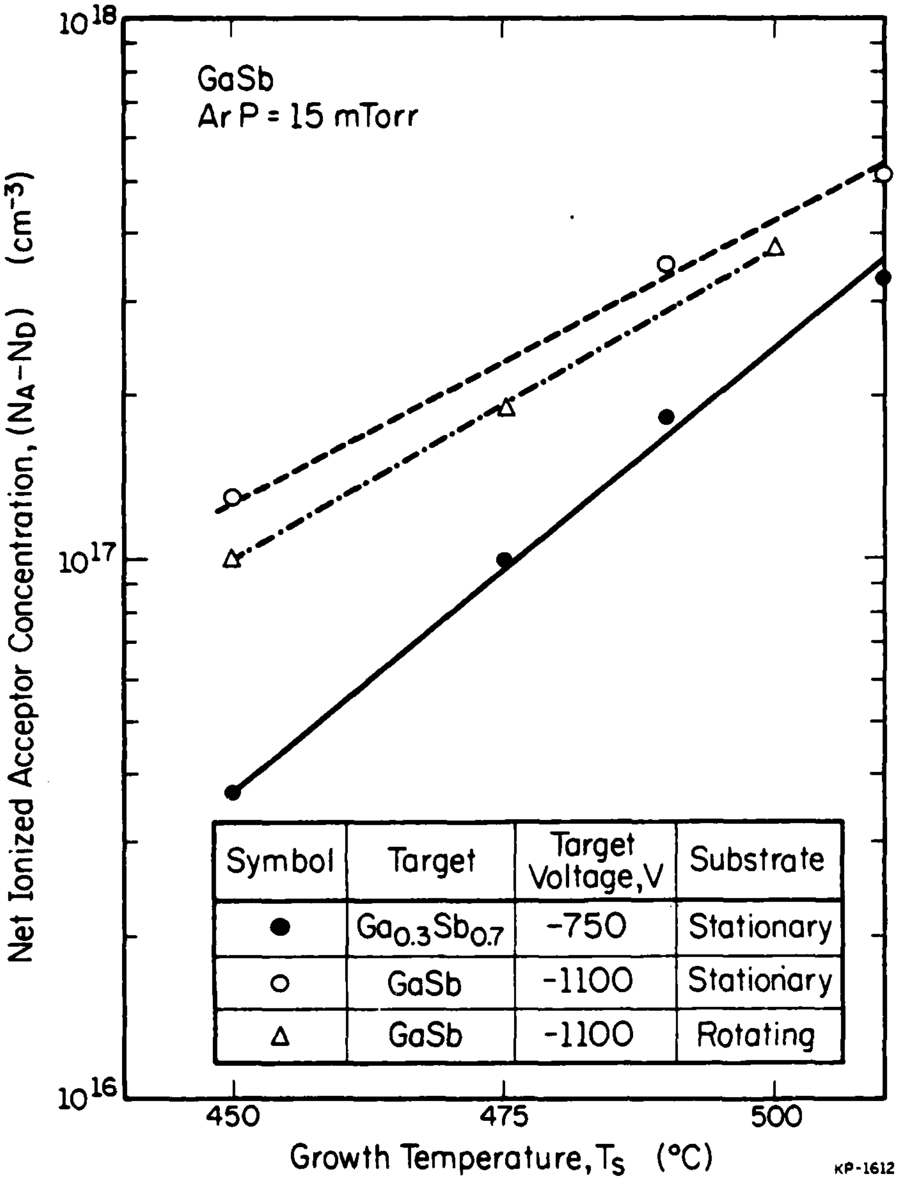

Fig. 5.3 The concentration of the net ionized shallow acceptors as a function of substrate temperature for GaSb films grown with different MTS target arrangements.

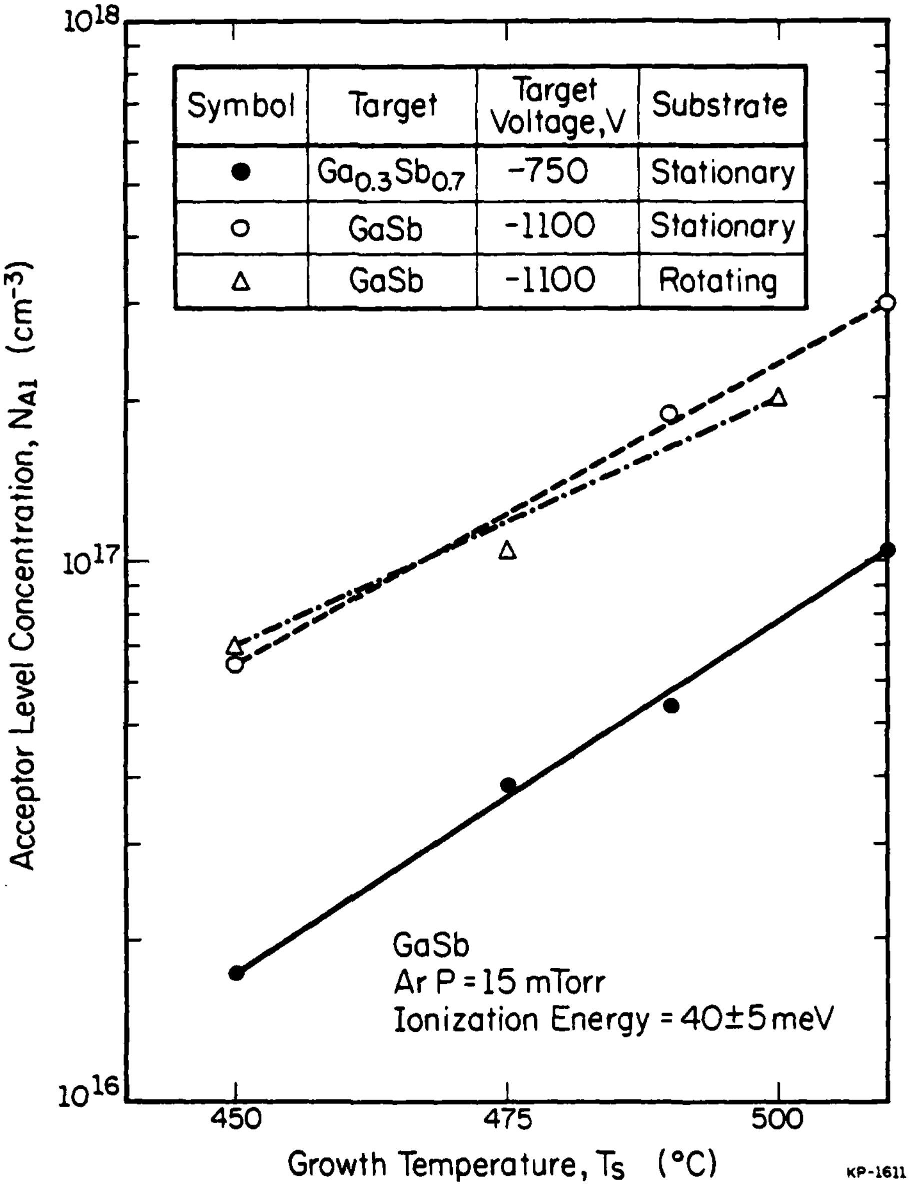

Fig. 5.4 The concentration of the intermediate acceptor level as a function of substrate temperature for GaSb films grown with different MTS target arrangements.

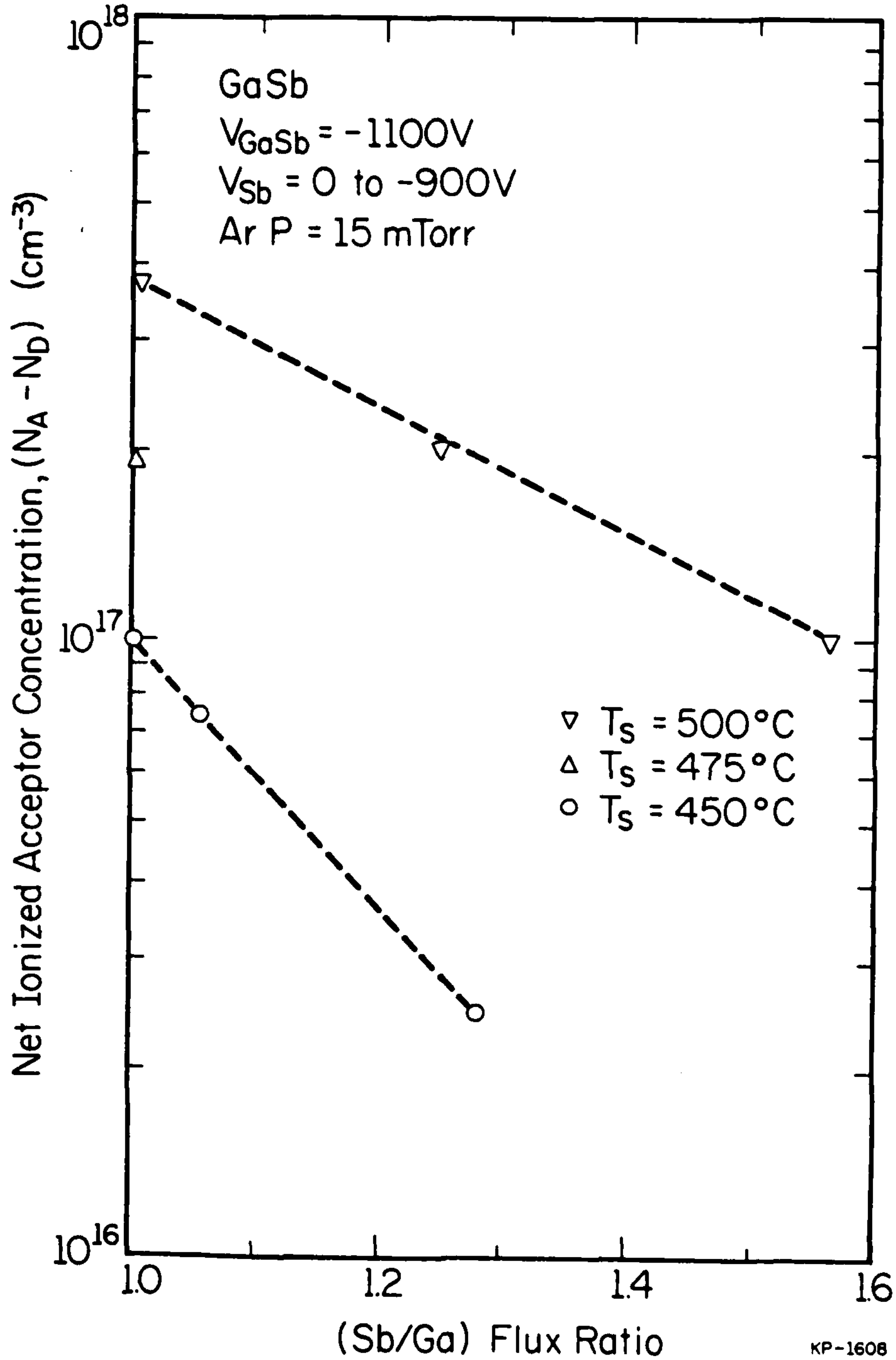

Fig. 5.5 The concentration of the net ionized shallow acceptors in MTS-grown GaSb films as a function of the Sb/Ga incident flux ratio.

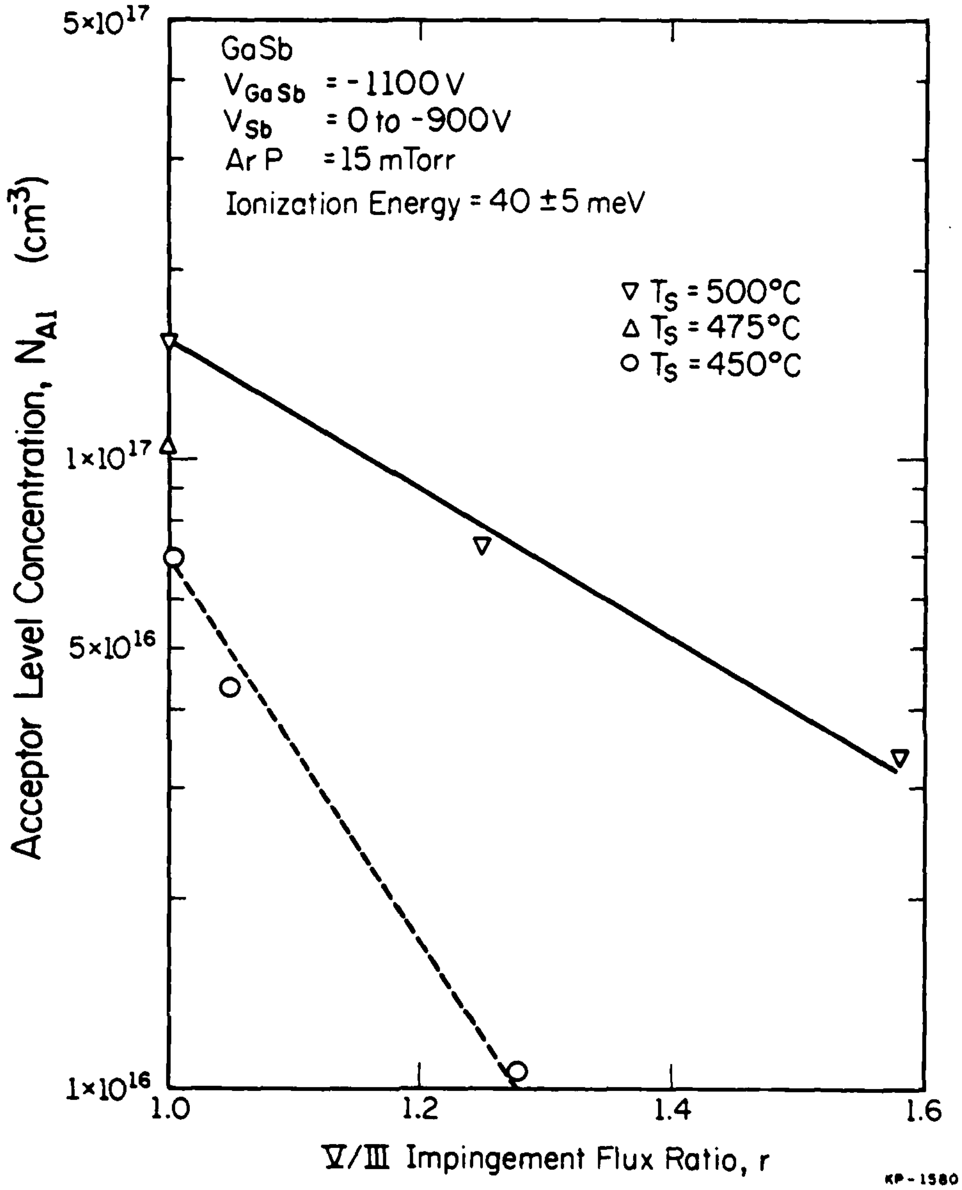

Fig. 5.6 The concentration of the intermediate acceptor level in MTS-grown GaSb films as a function of the Sb/Ga incident flux ratio.

as 3 7 X 10^{-3} and 8.3 X 10^{-3} at. % respectively.

The origin of the acceptor level at 80 meV is believed to be charged dislocation sites. N_{A2} was found to be independent of the particular target used, the sputtering gas purity, and the Sb/Ga incident flux ratio during film growth indicating that N_{A2} was not related to film chemistry. However N_{A2} decreased rapidly with increasing T_s and hence with higher structural perfection. The relationship between this level and film structure was further supported by the strong negative correlation between N_{A2} and the heavy-hole mobility. Since $\mu_h(300)$ was inversely proportional to the film dislocation density ρ_d, the average slope of the N_{A2}-vs.-$\mu_h(300)$ plot was used to estimate the fraction of active sites on dislocation lines, yielding a value of about 1/40.

The heavy-hole mobility μ_h was found to be thermally activated and exhibited a linear temperature dependence over a temperature range extending from ~20 to 200°K. μ_h was approximately constant for both lower and higher temperatures. Typical μ_h vs. T results are shown in Fig. 5.7. The observed temperature dependence in the intermediate range was accounted for by dislocation scattering as the limiting mechanism. This is consistent with electron microscopy studies of film structure revealing the presence of low-angle dislocation boundaries. The order of magnitude of the dislocation density calculated from the mobility data can by accounted for by the large film-substrate lattice mismatch.

The dislocation scattering mechanism was further supported by the observation of larger slopes in the linear μ_h-vs.-T region, and hence lower ρ_d values, for thicker films. As the film thickness increased, some of the dislocation lines originating at the interface bent under stress, and terminated at low and high angle dislocation boundaries. A similar decrease in ρ_d was also observed upon increasing the film growth temperature. This was explained as the result of the increased structural perfection at the film-substrate interface.

The nearly constant μ_h values at low temperatures ($\lesssim 20^\circ$ K) were shown to be associated with the degeneracy of the valence band. The mobility of degenerate carriers is proportional to the Fermi level regardless of the scattering mechanism. On the other hand, in the high-temperature region the magnitude of the measured hole mobilities in the films

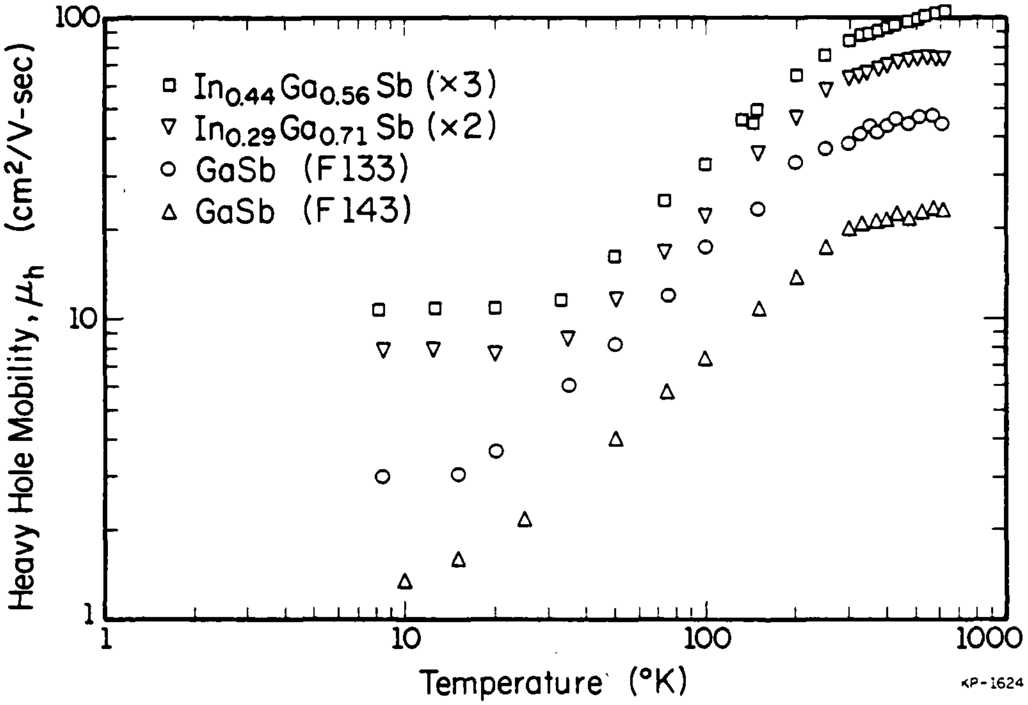

Fig. 5.7 The measured heavy-hole mobility in MTS-grown GaSb films versus temperature.

was too low for ionized impurity scattering or phonon scattering to have an appreciable effect. Although this region could be fitted in some cases by a potential barrier model, the barrier energy was too low to be significant at these high temperatures. Thus, the mobility behavior in this region is not understood at present.

In conclusion, we have shown that single-crystal GaSb films with hole concentrations as low as 5×10^{15} cm^{-3} can be grown by sputtering and that the Sb/Ga ratio in the film can be controlled within the narrow single-phase field using multitarget techniques. Carrier mobilities as high as 100 cm^2/V sec were obtained with the dominant scattering sites being dislocations introduced by the large film-substrate lattice mismatch. In one run, GaSb films were grown on Te-doped GaSb substrates and the resulting p-n junctions were found to exhibit good rectification with breakdown voltages of ~ 6 V.

5.3.2 Single Crystal Metastable $InSb_{1-x}Bi_x$*

The work reported here is the initial results obtained from the first detailed investigation of the growth of single crystal metastable semiconductors. While we have used $InSb_{1-x}Bi_x$ as a model material for reasons discussed below, we have already demonstrated the growth of other single crystal metastables such as $(GaSb)_{1-x}Ge_x$. We believe that the growth techniques we are developing are general and can lead to a new and unique class of materials. Thermodynamic studies of these metastable alloys are underway. The key feature in stabilizing the growth of these materials is the use of controlled low energy ion bombardment during deposition to modify elemental sticking probabilities (see section 5.2.2.) and to enhance elemental diffusivities (see section 5.2.1).

InSb crystallizes in the sphalerite zinc blende structure while InBi is a tetragonal semimetal with a maximum reported solid solubility in InSb of ~ 2.6 mole % [20]. The $InSb_{1-x}Bi_x$ system was chosen as a model to investigate for several reasons: (1) an extended solid solution

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would require both compositional and structural metastability, (2) the complete solid solubility of most pseudobinary III-V alloys indicates that the free energy difference between metastable $InSb_{1-x}Bi_x$ and the equilibrium state should be small, and (3) self-diffusion in III-V compounds is very slow indicating that metastable III-V alloys should exhibit reasonable thermal stability. In addition, choosing this system allows us to couple effectively with our previous work on the growth and characterization of single crystal InSb [21], GaSb [12], $In_{1-x}Ga_xSb$ [22,23], and InSb/GaSb superlattices [1,2] deposited by sputtering.

Epitaxial metastable $InSb_{1-x}Bi_x$ films with InBi concentrations up to 12 mole % have been grown on (110) GaAs substrates by multitarget rf sputtering. Low energy ion bombardment of the growing film was used to modify elemental Sb and Bi incorporation probabilities, σ_{Sb} and σ_{Bi}, through preferential resputtering in order to maintain overall stoichiometry and to allow the growth of single crystal extended solid solution alloys at elevated temperatures. The effects of the Bi to Sb impingement flux ratio, J_{Bi}/J_{Sb}, film growth temperature, T_s, and the Ar sputtering pressure, P_{Ar}, on the composition and structure of the as-deposited films as well as their metastable solid solubility were also investigated. Holding all growth variables except one constant in a given set of experiment, the ratio σ_{Bi}/σ_{Sb} was found to decrease with increasing J_{Bi}/J_{Sb}, increasing T_s, and increasing P_{Ar}. The metastable solid solubility limit increased with decreasing P_{Ar}. Single phase metastable films were n-type semiconductors with the 100° K carrier concentration increasing from 1.8×10^{17} cm^{-3} to 4.5×10^{17} cm^{-3} as the mole % of InBi was increased from 3 to 12.

All films were grown in a multitarget sputtering system which has been described in detail in previous JSEP progress reports. The system allows separate discharges to be established under each of several targets, in this case InSb and Bi targets were used, and the substrate platten may be rotated at a programmed rate through the discharges so that the film is deposited in a sequential "layer by layer" fashion. In general, whether the resulting film is a homogeneous alloy or compositionally modulated depends on the nominal layer thickness deposited per

target pass and the rate of interdiffusion. The latter term depends, in turn, on the film growth temperature as well as the amount of ion bombardment during deposition [1,2].

The elemental incorporation probability, σ, during film growth consists of two parts. A temperature dependent term ϕ which accounts for thermally stimulated desoprtion and a term Γ accounting for elemental resputtering rates. Γ is dependent on the total negative substrate bias with a secondary dependence on the growth temperature. As was expected from vapor pressure considerations, ϕ_{In}, Γ_{In}, ϕ_{Sb}, and Γ_{Sb} on InSb were found to be independent of T_s for the growth conditions used in these experiments. The values of ϕ_{Bi} and Γ_{Bi} on InSb, however, both decreased with increasing T_S in the range from 30^oC to 350^oC, a result which cannot be predicted simply from the vapor pressure of elemental Bi, $<10^{-7}$ Torr at 350^oC. Such behavior was caused by colligative effects between the Bi adlayer and the InSb-rich substrate due to submonolayer Bi coverage during growth. The large surface tension between Bi and InSb forced the deposited Bi atoms to nucleate three dimensionally on the InSb-rich surface. In addition, the tendency for nuclei growth normal to the surface increased at T_s, and hence the surface mobility of Bi adatoms, increased.

The vapor pressure of small particles is known to be several orders of magnitude larger than the vapor pressure of bulk material due to the increased contribution of the surface free energy to the total free energy of the particles. The desorption rate of Bi thus increased for values of T_s at which the bulk vapor pressure was negligible. The increased tendency for three-dimensional growth with increasing T_s resulted in a decrease in the fractional surface area covered by Bi, and thus in a decrease in Γ_{Bi}.

Preferential sputtering of group V elements from the growing film was observed whenever an excess concentration was present. The magnitude of Γ_V was found to increase with increasing substrate bias during the growth of In(Sb,Bi) films from group V-rich fluxes. The effect always occurred in such a manner as to attempt to preserve film stoichiometry. In no case was there any evidence for preferential sputtering from stoichiometric single phase compounds.

The preferential resputtering of excess group V elements in the present experiments resulted in a decrease in both σ_{Bi} and σ_{Sb} as the Bi/Sb flux ratio increased. As shown in Fig. 5.8, however, σ_{Bi} decreased faster with increasing J_{Bi}/J_{Sb} than σ_{Sb} did. The magnitude of this differential preferential sputtering effect was too large to be explained simply from heat of sublimation and momentum transfer considerations. In fact, the yields of elemental Bi and Sb are expected to be within 25% of each other. Therefore, we believe the rapid decrease of σ_{Bi}/σ_{Sb} with increasing J_{Bi}/J_{Sb} is primarily an artifact due to the method of film growth.

In these experiments, $InSb_{1-x}Bi_x$ films were grown by alternately depositing approximately one monolayer ($\sim$ 3.7 Å) of InSb in an rf discharge followed by the deposition of between 0 and 0.6 monolayers (0 to $\sim$ 1.9 Å) of Bi in a dc discharge. As the growing film rotates out of the dc discharge, there is a partial monolayer of Bi on an $InSb_{1-x}Bi_x$ surface. Some of the deposited Bi was thermally desorbed, but none was resputtered until the substrate was subjected to ion bombardment in the rf discharge.

As the film entered the rf discharge where the induced negative substrate potential V_i was $\sim$ 75 V for P_{Ar} = 15 mTorr (see section 5.2.2), preferential resputtering reduced the amount of excess Bi concomitant with the initiation of a new In and Sb deposition cycle. The remaining excess Bi as well as the impinging Sb competed for available In atoms in order to become incorporated into the $InSb_{1-x}Bi_x$ phase. Resputtering continued during the entire time that the growing film was in the InSb discharge with excess group V atoms, both Bi and Sb, being removed preferentially. Because of the initial elemental Bi surface coverage, the fraction of resputtered Bi was larger than that of Sb.

Mass balance equations were developed to describe the growth of $InSb_{1-x}Bi_x$ films by MTS. From this analysis it can be shown, in agreement with experiments, that at a critical value of J_{Bi}/J_{Sb}, which decreases as the amount of ion bombardment of the substrate increases, preferential Bi and Sb resputtering becomes insufficient to maintain film stoichiometry and excess group V elements form metallic precipitates

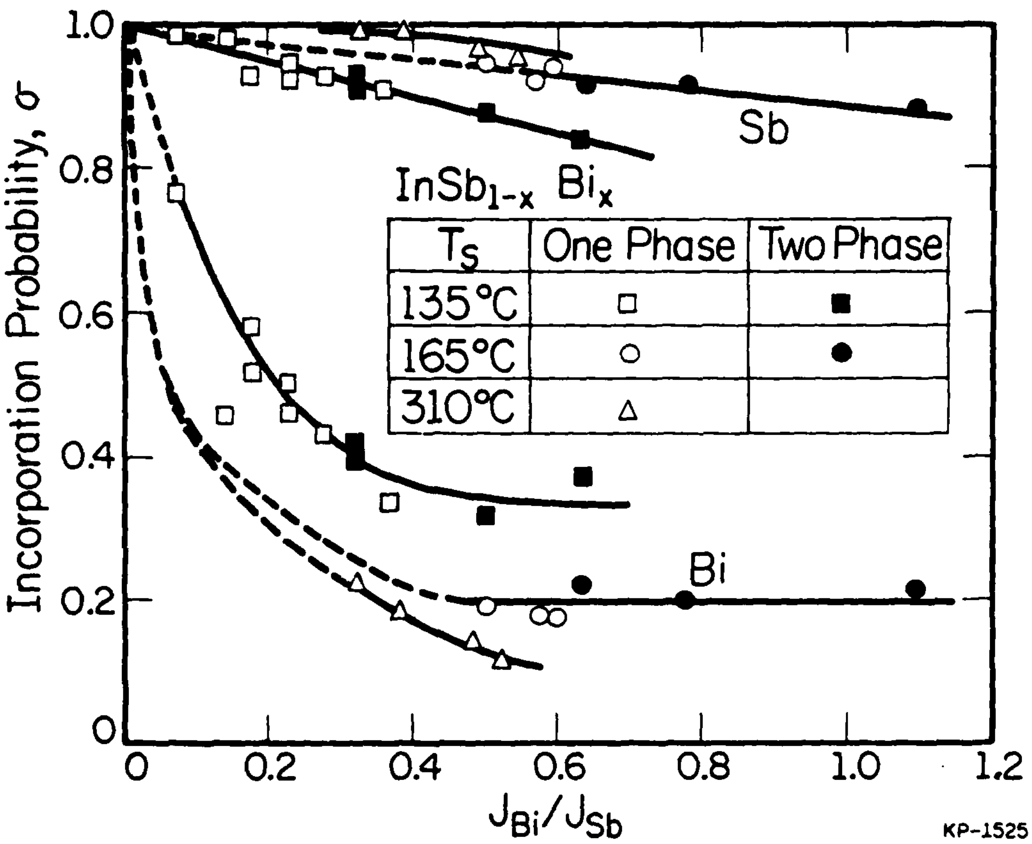

Fig. 5.8 The incorporation probabilities of Sb and Bi as a function of the Bi/Sb flux ratio and substrate temperature during the growth of $InSb_{1-x}Bi_x$ films.

in the $InSb_{1-x}Bi_x$ matrix. Increasing the sputtering pressure, P_{Ar}, at which such two phase films were grown resulted in a decrease in the amount of InBi incorporated into the $InSb_{1-x}Bi_x$ phase due to a decrease in ion bombardment during growth.

Increased ion bombardment of the growing film results in more complete mixing due to increases in adatom surface mobility as well as knock-in effects. Enhancements in diffusion rates of up to four orders of magnitude above thermal diffusion values were measured by Eltoukhy and Greene [1,2] in the InSb-GaSb system using similar MTS deposition parameters. Such enhanced adatom mobility combined with preferential resputtering of excess group V atoms increases the probability of a given Bi adatom being incorporated into an $InSb_{1-x}Bi_x$ lattice site rather than agglomerating to form a second phase.

The maximum amount of InBi incorporated into a stoichiometric one phase In(Sb,Bi) film was controlled by the amount of ion bombardment during deposition. We believe that the maximum solid solubility obtained in these experiments, 12 mole % InBi in (110) oriented In(Sb,Bi), is not a fundamental limit. It should be possible to grow metastable single phase $InSb_{1-x}Bi_x$ films with $x > 12$ mole % by further increasing the amount of ion bombardment at the growing film through an increase in V_s or a decrease in sputtering pressure. The absolute limit will occur only at values of x large enough such that the strain and chemical driving forces for equilibrium two phase formation overcomes the self-diffusion and surface energy activation barriers for the establishment of the second phase.

Optical and electrical measurements carried out on single crystal $InSb_{1-x}Bi_x$ films indicated that they were degenerate n-type semiconductors. The degeneracy was expected since even intrinsic InSb is degenerate at 300° K due to its small band gap ($E_g \simeq 0.18$ eV at 300° K) and large hole-to-electron effective mass ration ($m_h^*/m_e^* \simeq 14$). The addition of InBi further decreases E_g. Temperature dependent Hall effect measurements indicated that the dominant charge carrier scattering sites were dislocations resulting from the large lattice mismatch between $InSb_{1-x}Bi_x$ and GaAs. The activation energy of these barriers was 0.02 eV. Similar results were obtained previously for sputter deposited

single crystal InSb [21] and GaSb films on GaAs [12]. The carrier concentration of the $InSb_{1-x}Bi_x$ films ranged from $n = 3 \times 10^{16} cm^{-3}$ to $1 \times 10^{18} cm^{-3}$ with p-type compensation. A least squares fit of the optical band gap data indicated that a semiconductor to semimetal transition occurs at a composition of $\sim InSb_{0.88}Bi_{0.12}$.

5.3.3 Growth on InN in Mixed Ar + N_2 Discharges: Mechanisms of the Reactive Sputtering of In*

Optical absorption and emission spectroscopies have been used for in-situ investigations of processes occurring in the plasma and at the electrode-gas interfaces which control the reactive sputter etching of In targets and the reactive deposition of InN films in mixed Ar + N glow discharges. The range of sputtering parameters investigated was: dc target voltage = -2.5 kV; total sputtering pressure, P, from 30 to 70 mTorr; N_2 mole %, C_{N_2}, from 0 to 1; and target to substrate separation, d, from 3 to 6 dm. Under these conditions, no indication of nitride formation at the target surface or sputter ejection of InN molecular species was obtained. Increasing C_{N_2} at a constant value of P decreased the target sputtering rate R. This decrease was due primarily to a decrease in the ion current, i_T, caused by thermalization of low energy electrons in the plasma through excitation of vibrational modes in molecular N_2. The resulting decrease in the electron density was also responsible for quenching the optical emission intensity from atomic species in the negative glow. On the other hand, enhanced emission from sputtered In atomic transitions favorable for excitation by N_2^m metastables and N_2^+ ions were observed in the cathode fall and negative glow regions, respectively.

The nitrogen concentration in the deposited films, as determined by x-ray photoelectron spectroscopy and x-ray diffraction, was found to depend strongly on C_{N_2}, P_{N_2}, and d. The latter dependence was due to the position of the growing film surface with respect to the negative glow region where most of the atomic N is formed through the reaction $N_2^+ + N_2 \rightarrow N_2 + N^+ + N$. In short mean free path discharges this is the primary mechanism of nitrogen incorporation since In does not chemisorb N_2, only N. InN films grown on glass substrates at $\sim 80^{\circ}C$ were

*This work was supported by the National Science Foundation under Grant DMR-76-20640.

found to be polycrystalline n-type semiconductors with a room temperature resistivity of 40 mΩ-cm, a carrier concentration of $\sim 5 \times 10^{18}$ cm^{-3}, and an electron mobility of ~ 20 cm^2/V-sec. The index of refraction at 1 μm and the room temperature direct band gap were found to be 2.85 and 1.65 eV, respectively.

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6.1 Introduction

The long range objective of this research is to originate and analyze new microacoustic wave principles that will lead to significant device applications. The work has been focused on the development of more universal and complete transducer models, fundamental studies of surface acoustic wave scattering, and the development of a new class of microwave acoustic devices based on nondispersive waves propagating along a substrate edge.

6.2 Line Acoustic Waves in GaAs*

Line Acoustic Waves are being studied in the substrate GaAs to investigate wave-charge carrier interactions. In particular, the possibility of the synchronous transport of charge using the traveling wave electric field of LAW is of interest. Linewaves with electric fields ten times greater than the estimated value required to produce synchronous transport of electrons have been generated in GaAs:Cr. Simple experiments designed to detect-transport have thus far yielded inconclusive results.

A primary objective of the work during this period has been to produce LAW of sufficient amplitude to transport charge. Using a conservative estimate for the mobility of electrons in GaAs, it is seen that a traveling wave electric field of approximately .2 KV/cm minimum is required.

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Since GaAs is only weakly piezoelectric, past work has mainly been concerned with the realization of efficient transducers. Along these lines, the sawtooth transducer shown in Figure 6.1 has been found to be an effective generator of linewaves with an acoustic Q approaching that obtainable with a comparable surface wave interdigital transducer [1]. Another important factor in the minimization of transducer insertion loss is the piezoelectric coupling of the particular crystal cut used. Studies directed toward 100 and 110 cut crystals have shown that 110 cut substrates cleaved in the 110 plane along the 111 direction yield a maximum in the coupling coefficient with respect to the other possible orientations. Similar results have been observed for the case of surface waves in GaAs [2]. The 60° wedge obtained with this orientation has the added advantage of accentuating the tight confinement of the linewave near the apex of the wedge resulting in electric fields greater than those achieved with 90° wedges.

Initial investigations of charge transport have concentrated on chromium doped GaAs primarily, because the available undoped material exhibits significant conductivity which hinders excitation of LAW. Due to the rather impure composition of the undoped substrates available [3], successful depletion biases are estimated to be of the order of several hundred volts. The Cr doped substrates, exhibiting much higher resistivity, do not pose this problem.

Preliminary tests to detect the presence of charge transport have been performed on 110 cut GaAs:Cr linewave devices. Although the traveling wave electric field in these devices was estimated to be an order of magnitude greater than the synchronous field required for transport, no interaction as of yet has been observed. Possible causes of inhibited transport are the trapping capabilities of the chromium centers in the material, lack of current path provisions in the device and surface state losses. These factors are presently under investigation.

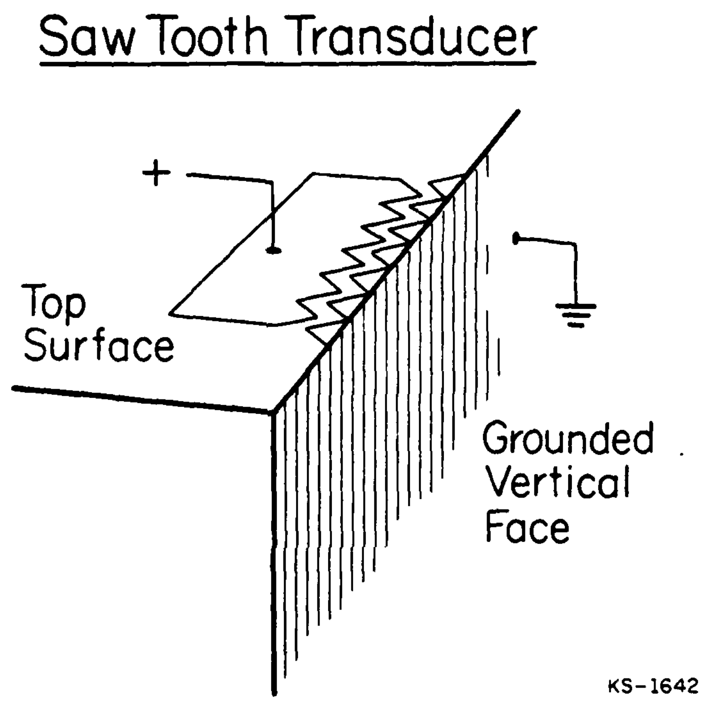

Fig. 6.1 Sawtooth Transducer

6.3 Piezoelectric and Elastic Scattering of Surface Acoustic Waves*

The objective of this work is to develop a theoretical description for the propagation of surface waves in the presence of a periodic array of electrically loaded electrodes at the surface.

A significant problem in the analysis and design of surface wave transducers and reflectors is to describe the propagation of surface waves in a periodic array of electrodes. This is commonly done using a mismatched transmission line model in which the velocity and impedance are assumed to change under the electrodes as compared to the free surface regions. However, both the change in velocity Δv and the change in impedance ΔZ are obtained empirically. The objective of this program is to develop a theoretical approach to calculate ΔZ and Δv directly from the material parameters of the substrate and the electrodes.

ΔZ represents the reflection from an electrode while Δv represents the change in the propagation constant of the wave due to the electrode. Physically, both these effects are described as the generation of surface waves by induced sources arising from the interaction of the incident wave and the electrode. The incident wave, A_i [Figure 6.2] in the presence of the electrode gives rise to stresses and charges which act as secondary sources and generate waves in both directions. The backward wave A_- is equal to the reflected wave A_r and is modeled by assuming an impedance mismatch ΔZ. The forward wave A_+ is added to the incident wave A_i to form the transmitted wave, A_t. Usually A_+ is 90^o out of phase with A_i so that A_t is phase shifted with respect to A_i. This phase shift is modeled as a change in velocity Δv.

Both the piezoelectric scattering (due to induced charges) and the elastic scattering (due to induced stresses) have been calculated theoretically and are described in References 4, 5, and 6. Preliminary work indicates good agreement with experimental data.

*This work was supported by the Rome Air Development Center, Deputy for Electronic Technology under Air Force Contract Number F19628-78-C-0040.

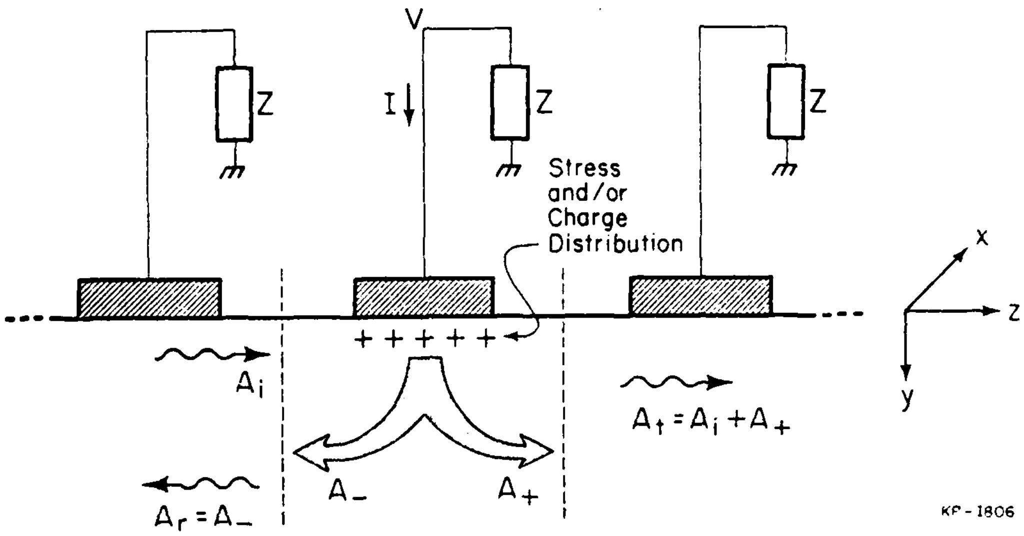

Fig. 6.2 Reflection and phase-shift of surface waves due to regeneration by induced sources.

6.4 Scatter Matrix Analysis of SAW Reflectors and Transducers*

A recently derived SAW electrically loaded reflector array analysis is used to calculate the 3 port scatter matrix of a single electrode [4]. This is used to calculate a 3 x 3 matrix for a complete transducer by cascading single electrode matrices [7]. The model input parameters are electrical load, transducer geometry and material parameters. Tap interactions and regeneration are taken into account by the cascading process. The input admittance, electrical to acoustic transfer function, acoustic to acoustic transfer function, and reflectivity as a function of frequency are found directly in the transducer scatter matrix. Comparison of theory and experiment show close agreement including the characteristic frequency shift. Figure 6.3 is the input conductance of a 156 electrode transducer on $LiNO_3$. This is compared with the experimental results of Jones and Hartmann [8]. Single and double electrode transducers (3rd harmonic included) can also be analyzed with varying electrical loads.

6.5 Analysis of Nonperiodic Transducer Structures*

The central problem in calculating the response of SAW interdigital transducers is to calculate the charge distribution from the electrostatic field equations. For periodic transducers with known voltages, the charge distribution is given by the product of an array factor, which is the fourier transform of the voltages, and an element factor, which is calculated once using field theory [9,10,11]. In this case the field equations need not be solved anew for each transducer. For transducers with floating electrodes, this method cannot be used directly because not all of these voltages are known. We have demonstrated that a circuit model of the transducer can be used to calculate these floating electrode voltages so that this method can still be applied [12].

Unfortunately, for nonperiodic transducers, the charge distribution previously could only be found by solving the field equations

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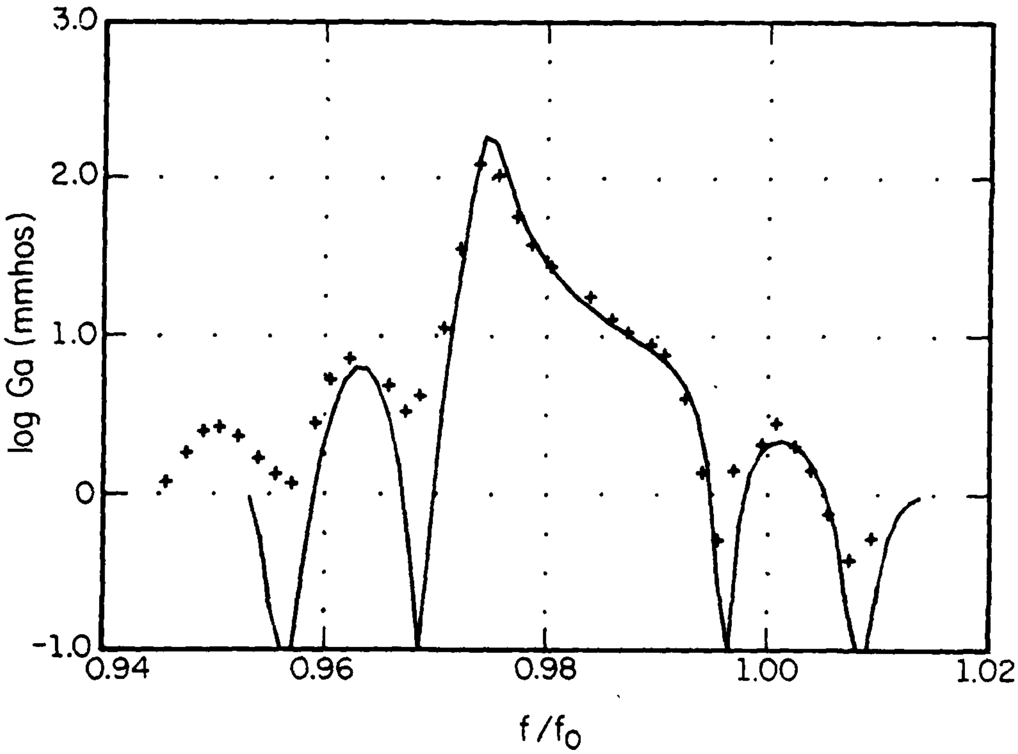

Fig. 6.3 Calculated input conductance of 156 electrode transducer compared with experiment (+).

anew for each individual transducer, using the appropriate surface boundary conditions [13,14,15]. By dividing each electrode and gap into a periodic array of many small electrodes, we can now model the transducer by a circuit similar to the one used for periodic transducers with floating electrodes [16]. We can find the potential and charge distribution for any arbitrary transducer by using simple circuit theory techniques to find the charge and voltage on the small electrodes. We have used this circuit model to calculate the charge distribution for single and double electrode transducers and the results compare very favorably to known analytical results calculated from field theory. Presently we are working to incorporate regeneration effects into our circuit model using the scatter matrix analysis techniques.

6.6 References

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7.1 Surface Chemistry*

Continuing emphasis in this area has been upon two related topics: (1) electron beam interactions with surface layers, and (2) molecular decomposition at solid surfaces. Activity in both areas has been vigorous, with new and interesting results achieved in the latter.

7.1.1 Kinetics of Molecular Decomposition on Solids

Unifying our investigations in the recent past has been a simple notion: the formation of monomolecular layers on solids can be directed by allowing beams of photons or electrons to interact with the surface. In our previous studies [1] we demonstrated that irradiation of methane (CH_4) with a He-Ne laser, set to excite the ν_3 asymmetric stretching mode of the gas, did not cause any noticeable enhancement of the decomposition at a rhodium surface. This result was quite unexpected and we have, therefore, continued exploring irradiation effects.

Of special interest in the decomposition of CH_4 is the excitation of overtone and combination bands. As is apparent in Table 7.1, such bands have energies comparable to the activation energy of 7 kcal/mole, observed for the decomposition of CH_4 in molecular beam experiments in this laboratory [2]. Unfortunately, laser sources in the appropriate wavelength domain are not readily available. We have, therefore, carried out

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Table 7.1 Infrared Active Bands of CH_4

Band	Center cm^{-1}	Vibrational Energy kcal/mole	Integrated Intensity $atm^{-1}cm^{-2}$
ν_4	1306	3.73	146
$2\nu_4$	2610	7.46	2.5
ν_2	2828	8.09	20
ν_3	3019	8.63	312
$\nu_2 + 2\nu_4$	4123	11.79	0.16
$\nu_1 + \nu_4$	4223	12.07	4.4 , 10
$\nu_3 + \nu_4$	4321	12.35	3.7
$\nu_2 + \nu_3$	4546	13.00	1.26
$\nu_3 + 2\nu_4$	5585	15.97	
$\nu_1 + \nu_2 + \nu_4$	5775	16.51	
$\nu_2 + \nu_3 + \nu_4$	5861	16.76	
$2\nu_3$	6005	17.17	1.76

exploratory experiments using a high pressure xenon discharge lamp, which excites transitions in the range 1.67-2.5μ. The results are shown in Fig. 7.1. It appears that with the sources available, no change in the rate of decomposition is detectable. Of the accessible transitions, only $2\nu_3$ has a well documented and sizable cross-section. From our measurements we can conclude that the sticking coefficient of CH_4 molecules in the second vibrational state of ν_3 must be less than 7×10^{-2} in order not to have been observed.

More detailed experiments to elicit the role of this similar excitations in molecular decomposition will depend upon the availability of high power, tuneable infrared sources. In the meantime, we are pursuing the mechanism of decomposition more indirectly, by studying the effects of isotopic substitution upon the rates of the thermally induced decomposition process. This we can do in detail by following the pressure decay in systems in which a freshly deposited rhodium film is exposed to a fixed quantity of gas. So far we have compared the reactivity of CD_4 and CH_4. As is apparent in Fig. 7.2, the barrier to the decomposition of the two molecules is quite different. It amounts to 4.9 kcal/mole for CH_4 and 8.7 kcal/mole for CD_4. This is quite outside the range of the zero point energies of the normal vibrations characteristic of the two molecules. However, the difference in barriers is partly compensated by the much larger prefactor observed for CD_4. The significance of these differences is not yet clear, but it is now certain that some quantal effect is involved. Further measurements, on other isotopes, are underway to help clarify how decomposition of polyatomic molecules occurs, and to what extent it can be altered by radiation.

Concomitant with these studies, we have also been carrying on work to examine molecular interactions on silicon surfaces. This has required a considerable construction effort, which is now nearing its end. Facilities and techniques for preparing high quality silicon wafers have been developed. Most important, a system has been built to examine electron beam interactions with crystals. This is shown schematically in Fig. 7.3. Its main part consists of stainless steel bell jar, built in our shop; this is evacuated by mercury diffusion pumps to allow argon sputtering of the sample without contamination. Facilities are provided

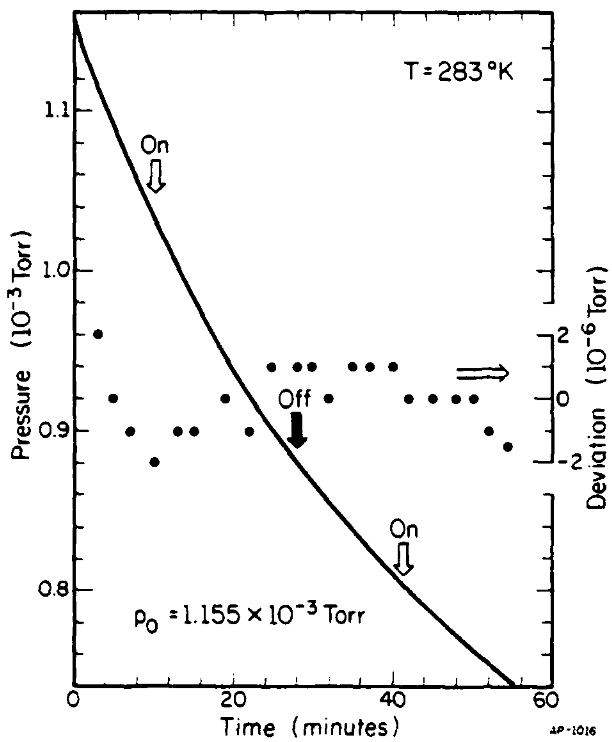

Fig. 7.1 Pressure changes for methane over rhodium under irradiation with a xenon arc. Ordinate at right gives deviations from expected decay. Arrows indicate periods of irradiation.

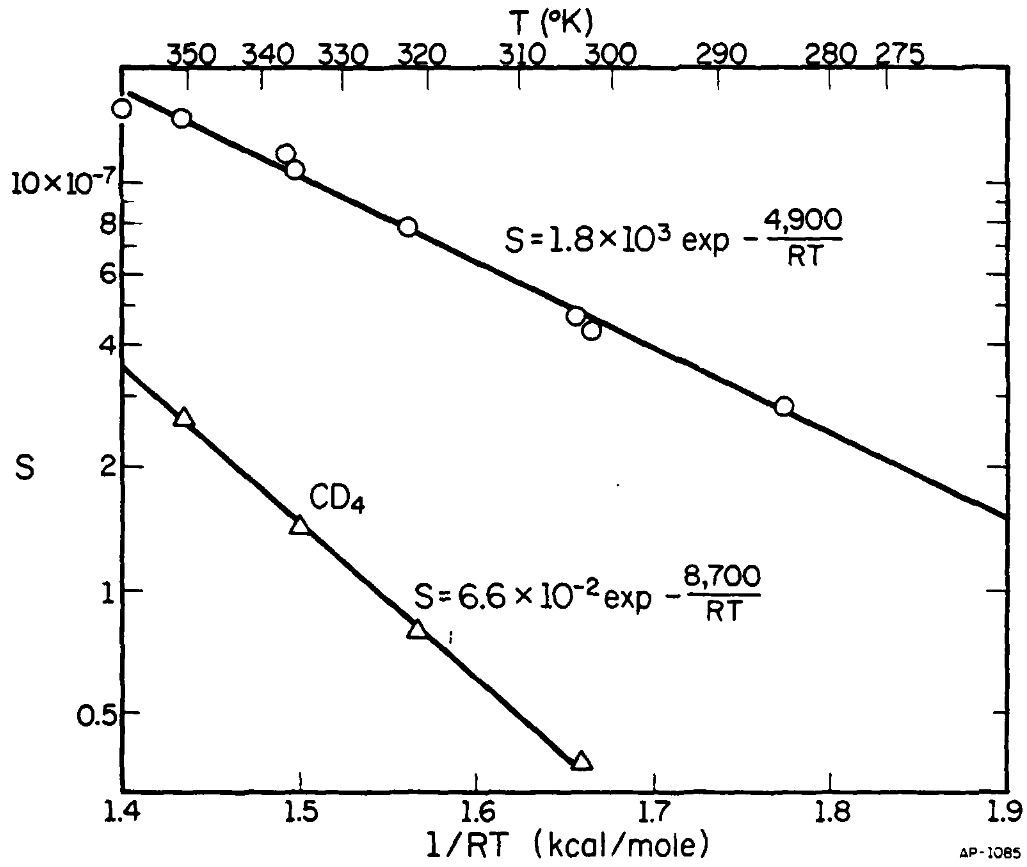

Fig. 7.2 Comparison of sticking coefficient s for decomposition of CH_4 and CD_4 on rhodium.

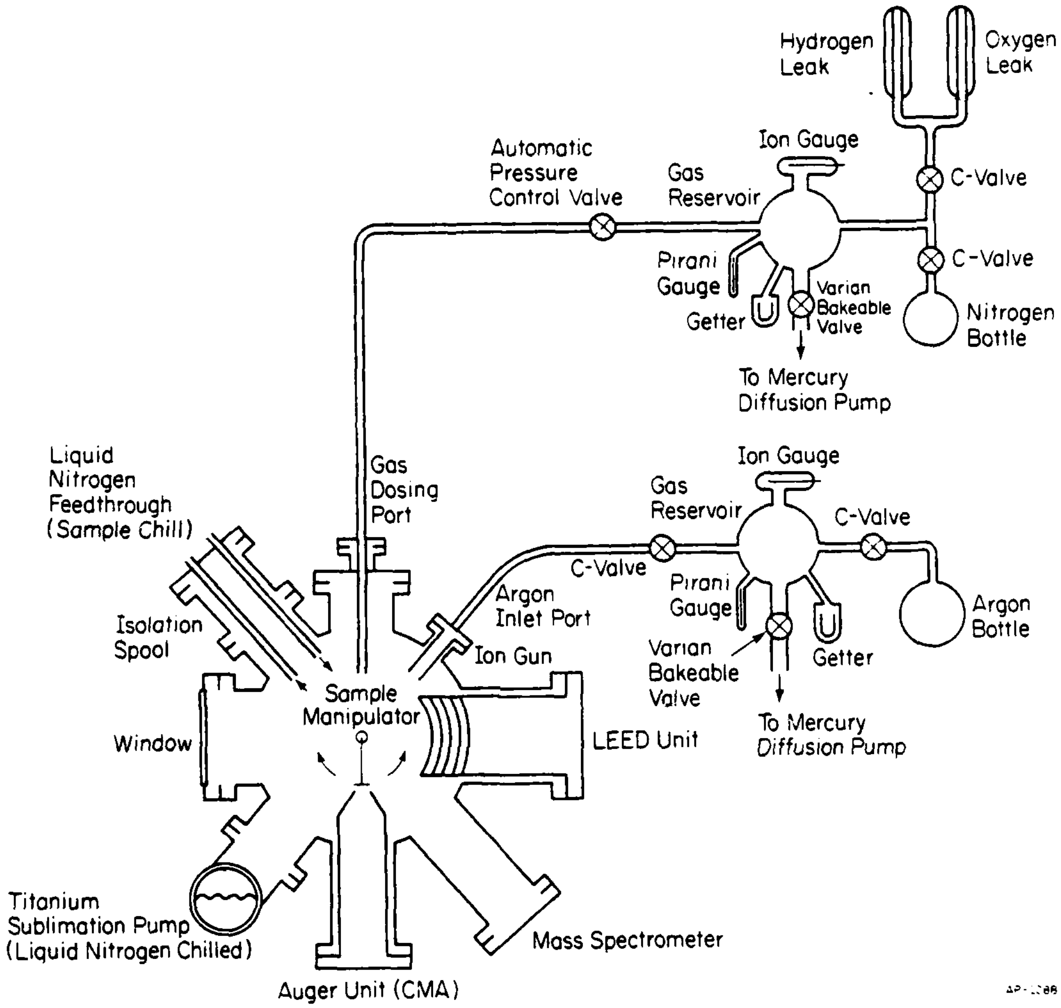

Fig. 7.3 Schematic of instrumentation for examination of electron beam effects on the formation of surface layers.

for the characterization of the surface by low energy electron diffraction, scanning Auger spectroscopy, and mass spectrometry. A glass system is coupled to the bell jar, to allow the introduction of gases under carefully controlled conditions. The various analytical instruments have been checked out individually, and introductory experiments, to probe the effects of electron bombardment on the formation of surface layers, are underway.

7.2 Atomic Exploration of Crystal Surfaces*

The continuing emphasis of our studies during the past year has been upon the atomic basis of material transport on solids. It now appears from the work below that the detailed mechanism of the atomic jumps occurring in surface diffusion can for the first time be successfully examined.

7.2.1 Jump Processes in Linear Diffusion

As already suggested last year [3], it is possible to learn how atomic jumps occur in linear diffusion by examining the distribution of distances covered by an atom during a fixed time interval. This is clear from Fig. 7.4, comparing the distance distribution for atoms that always jump to their nearest neighbor site with the distribution for atoms that span two atomic distances in each jump. The two are quite different. Techniques worked out here by M. Twig [4] make it possible to derive α, the frequency of single jumps, and β, the frequency of double jumps, from experimental observations of the distribution. Detailed measurements, shown in Fig. 7.5, have been carried out for tungsten atoms on the (211) plane of tungsten. They indicate that the ratio of double to single jumps amounts to only 1/10. In this system at least it appears that individual atomic jumps occur over short distances, comparable to the elementary spacing of the crystal substrate. The universality of this result is now being checked in a series of experiments with other materials.

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*This work was supported by the National Science Foundation under Grant DMR 77-23723 and by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contracts DAAG-29-78-C-0016 and N00014-79-C-0424.

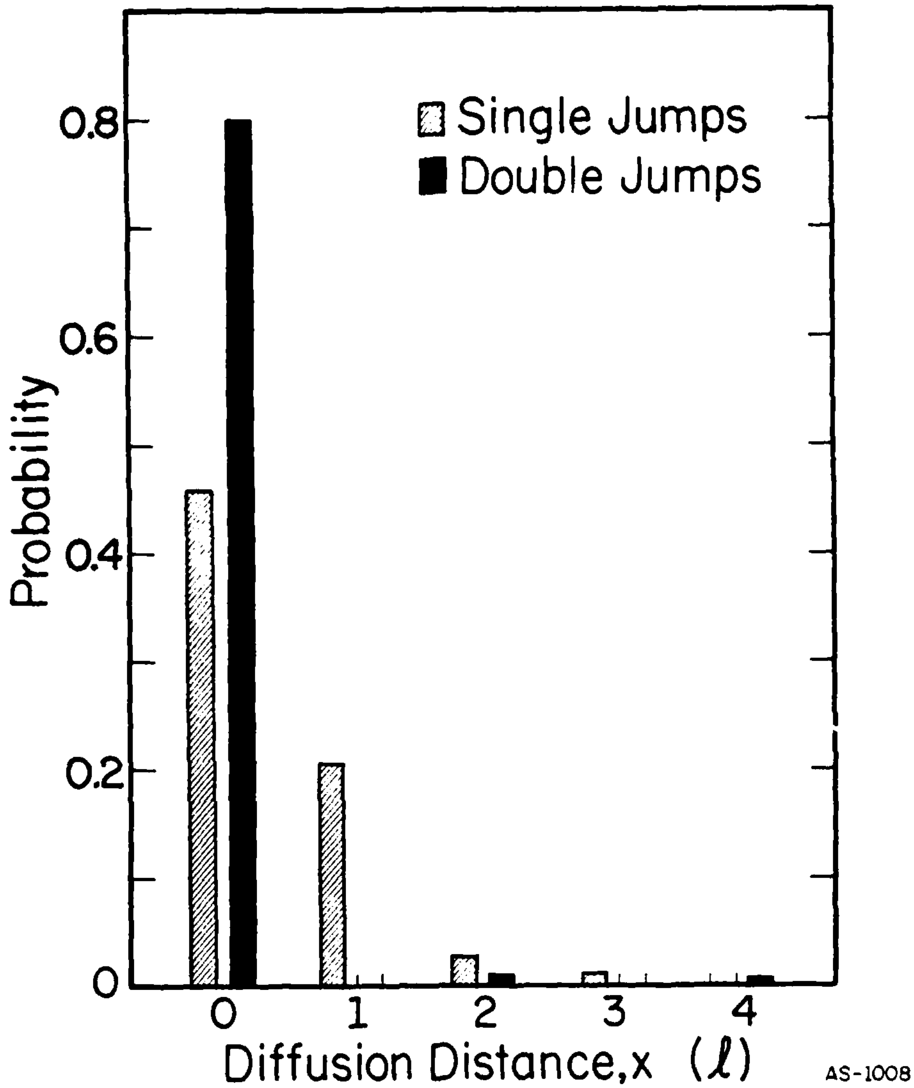

Fig. 7.4 Distance distribution for 1-dimensional diffusion via single and via double jumps.

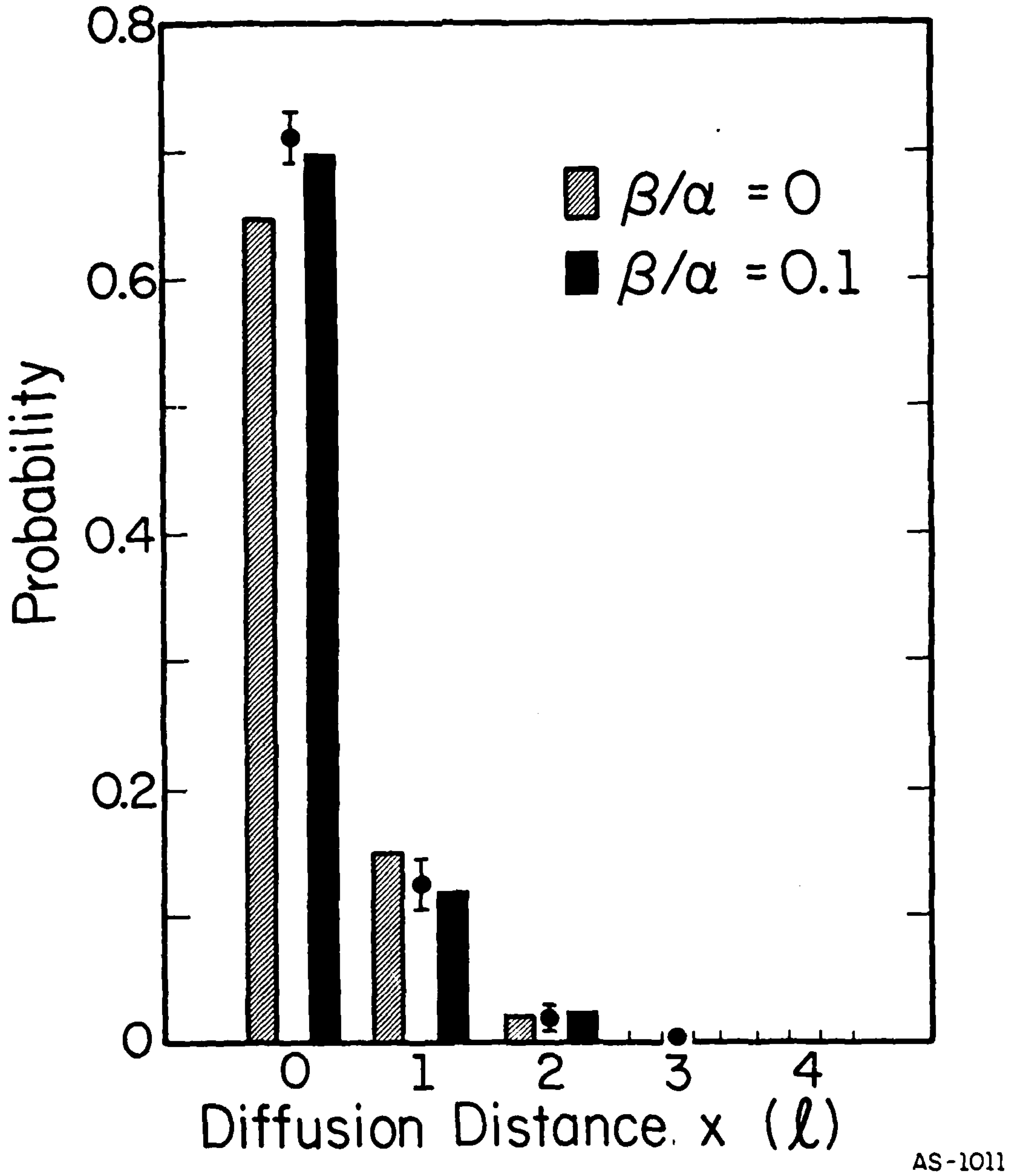

Fig. 7.5 Distance distribution for W adatoms on (211) plane of tungsten. Experiments are best fit by assuming the ratio of double to single jumps is 1/10.

7.2.2 Studies of Cross-Channel Jumping

On substrates such as tungsten and rhodium previously studied in this laboratory [5], it has been found that atomic motion on channeled planes like (211) on tungsten and (110) on rhodium always occurs along the channels made up of close-packed rows of lattice atoms. Recently, however, it has been shown that on the face centered cubic metals platinum and iridium, this is not always the case: on the (110) planes of these materials atomic jumps across the channels are often favored [6]. This, for example, is true for the motion of tungsten atoms on the (110) plane of iridium, as is evident from the photograph in Fig. 7.6 taken in the filed ion microscope. The puzzling question has been, how does such motion occur? Does the tungsten atom jump over a close-packed row, or does it just replace a lattice atom, pushing the latter into the adjacent channel?

To establish the events in cross-channel jumps, we have carried out experiments in an atom probe [7]. This instrument [8], shown schematically in Fig. 7.7 makes it possible to visualize individual atoms on the surface and then to establish their chemical identity by measuring their time of flight when ionized suddenly by a high field pulse. If tungsten atoms carry out cross-channel jumps on Ir(110) by replacing a lattice atom, then after the initial jump, the atom that appears in an adjacent channel should be iridium, not tungsten. By checking the chemical identity of an atom before and after the diffusion, we should, therefore, be able to establish how such jumps occur.

Preliminary experiments have been carried out by J. D. Wrigley and the resulting mass distributions are shown in Fig. 7.8. After diffusion, the mass of the adatom appearing in the adjacent channel has changed by ≈ 7, which is very close to the change expected from tungsten to iridium. This result strongly suggests that atomic motion in this system involves interchange with the lattice. Further extensive tests of this model are now underway, to establish this result more securely and also to explore how widespread interchange with the lattice is during diffusion.

Fig. 7.6 Field ion observations of tungsten diffusion on Ir(110). (a) Clean (110) plane. Channels run horizontally across the plane. (b) Tungsten atom deposited on (110). (c) Atom has diffused across the channels, moving up on the picture. (d) Atom has returned to its initial location after another jump.

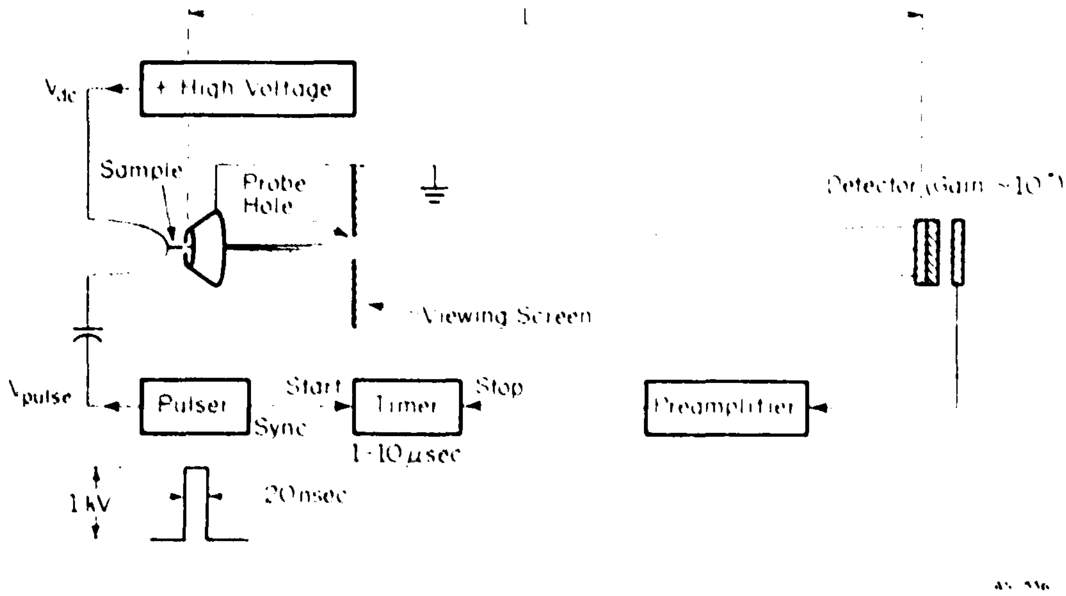

Fig. 7.7 Schematic of atom probe.

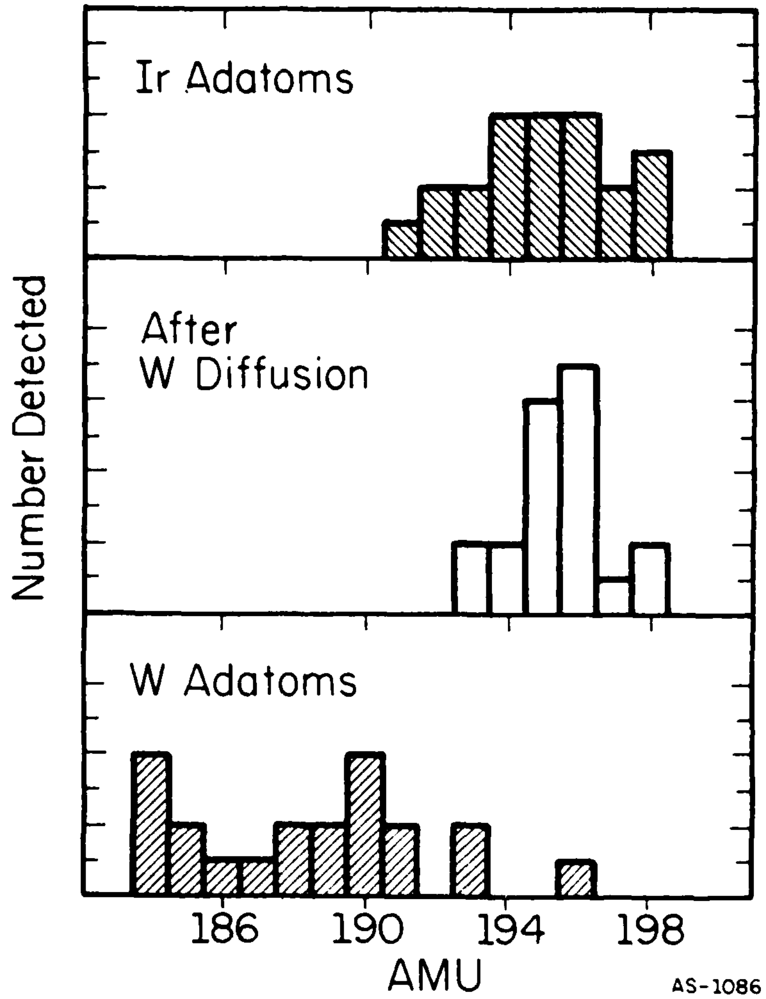

Fig. 7.8 Atom probe measurements on Ir(110).

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8.1 Introduction

During the present grant period, we have directed our attention to several important and fundamental problems related to the design of dielectric-based integrated circuits for millimeter waves. First, we have developed some new designs for transitions from metal-to-dielectric waveguides, for both the image and inverted-strip types. Second, we have investigated the possibility of using waveguides whose dimensions allow more than one propagating mode in the guide. Third, we have designed and tested a number of dielectric antennas suitable for integration with dielectric waveguides. Fourth, we have been experimenting with active devices, e.g., mixers and oscillators in the frequency range of 60 GHz and above, up from the 30 GHz range which we successfully studied last year. Fifth, we have developed a new, highly sensitive probe suitable for measuring near fields of dielectric waveguides and components.

In the theoretical end, we have developed accurate procedures for computing the mode characterizations which include the cut-off frequencies and the field distributions for the higher-order modes. We have also been supporting the experimental projects mentioned above with theoretical efforts necessary for evolving new designs.

During the reporting period, the Fourier Transform approach has been extensively used for solving electromagnetic radiation and scattering problems. New accuracy tests have been developed and applied. In addition, iterative methods for systematically improving a given asymptotic solution have been devised.

8.2 Millimeter Wave Integrated Circuits*

8.2.1 Transition from Metal to Dielectric Waveguides

The design of transitions between metal and dielectric waveguides is an important problem that must be solved before a total integrated circuit system, e.g., a receiver, can be successfully built. Little or no information is presently available in the literature on how tc design a transition which has a low insertion loss over a moderately wide bandwidth.

The design for the transition was carried out initially at X-band and then scaled up to the millimeter wavelengths at E-band (80-85 GHz). After testing a number of different transitions, a launching horn-type configuration, shown in Fig. 8.1, was employed. A parameter study of the length and flare of the horn and the taper length of the dielectric was carried out with a view to developing an optimum design. Figure 8.2 shows the overall insertion loss at X-band for two transitions for metal-to-plexiglass waveguide with the latter tapered at both ends (See Fig. 8.3). The loss per unit length of the dielectric guide was deduced from the results shown in Fig. 8.2 and compared with the theoretical values. This comparison is shown in Fig. 8.4a. Next, the transition loss was calculated and compared with the measured results both of which are shown in Fig. 8.4b. The solid curve in this figure shows the loss due to two dielectric tapers fitted back-to-back into a standard X-band guide.

Figure 8.5 shows the return loss curves for two different types of dielectric tapers, viz., the taper in both planes, and in the H-plane only. This result is useful for designing tapers at E-band where the waveguide dimensions become unmanageably small to conveniently introduce tapers in both planes, particularly the E-plane.

The dimensions of the E-band taper designed to operate in the 80-85 GHz range are shown in Fig. 8.6. The insertion loss for this taper is shown in Fig. 8.7; it should be noted that the loss per transition is on the order of 0.5 db, although clearly, this is a maximum value

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contracts DAAG-29-78-C-0016 and N00014-79-C-0424 and by the U.S. Army Research Office under Grant DAAG 29-77-G-0111.

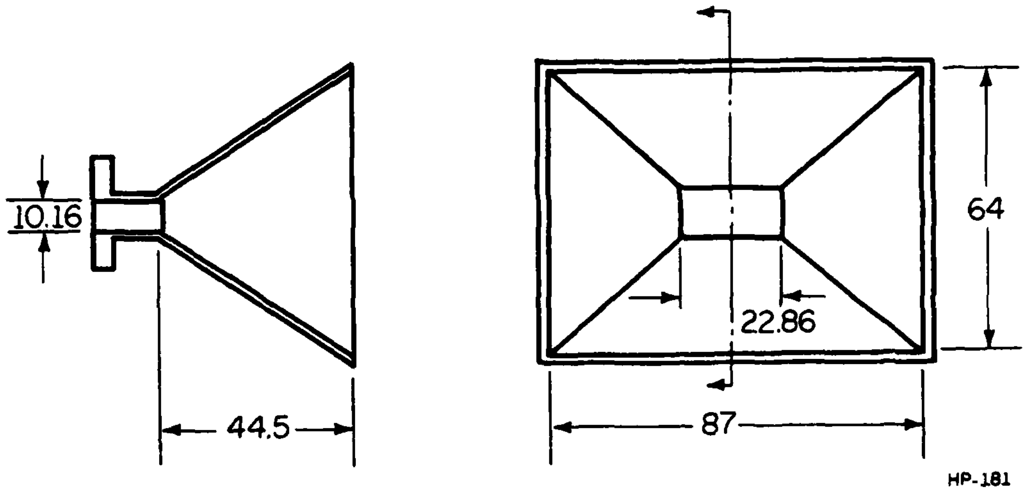

Fig. 8.1 Inside Dimensions (mm) of the X-band horn.

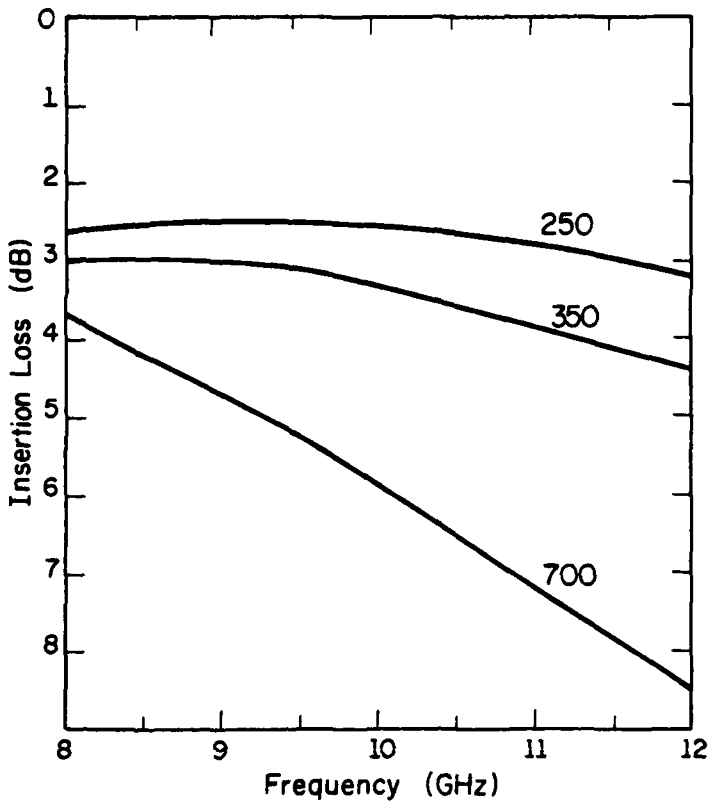

Fig. 8.2 Insertion loss vs. frequency for various lengths of line. Line lengths shown in mm.

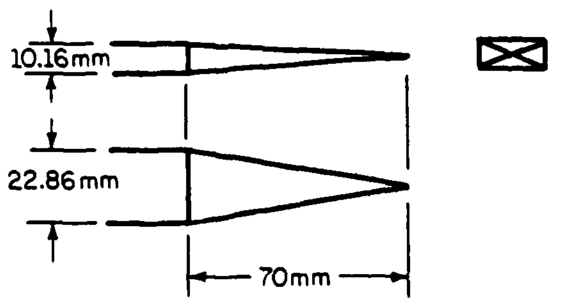

Fig. 8.3 Dielectric taper.

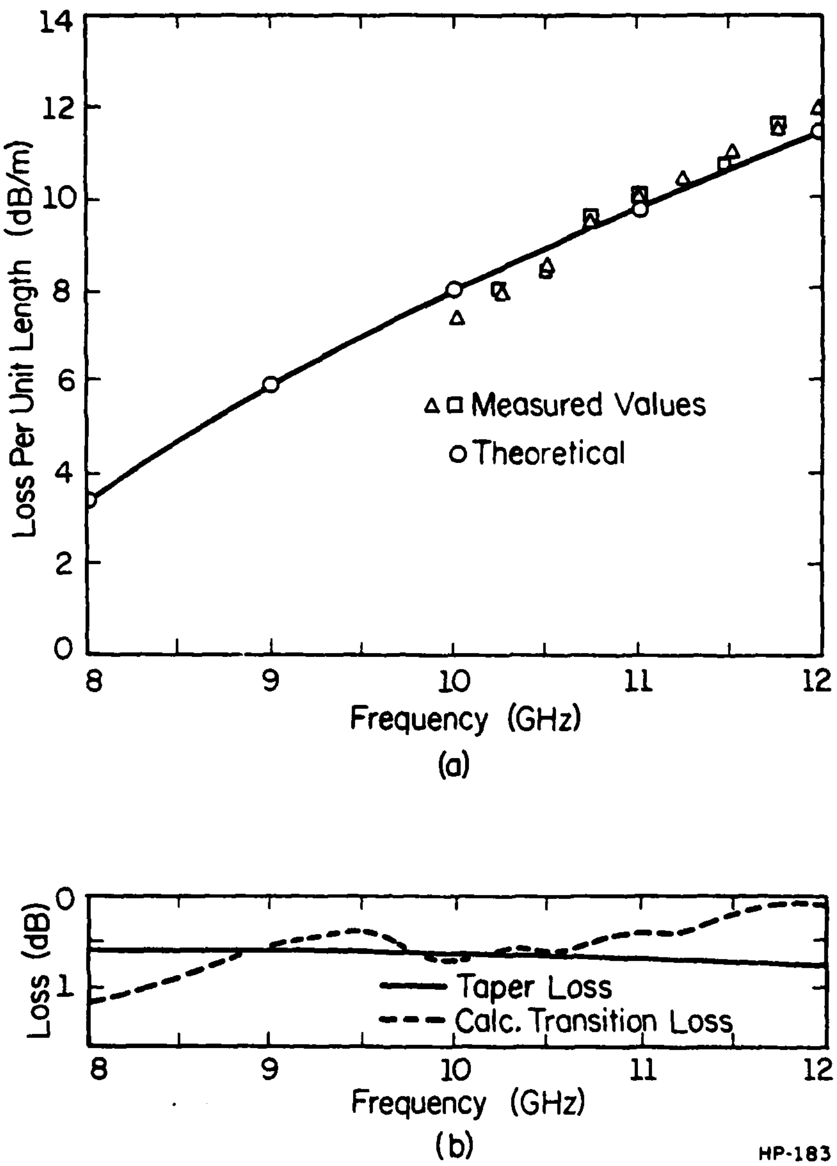

Fig. 8.4 Loss per unit length for dielectric guide (a) calculated: —o— ; measured: □ & Δ. (b) measured loss in the dielectric tapers: ——— ; calculated transition loss: -----.

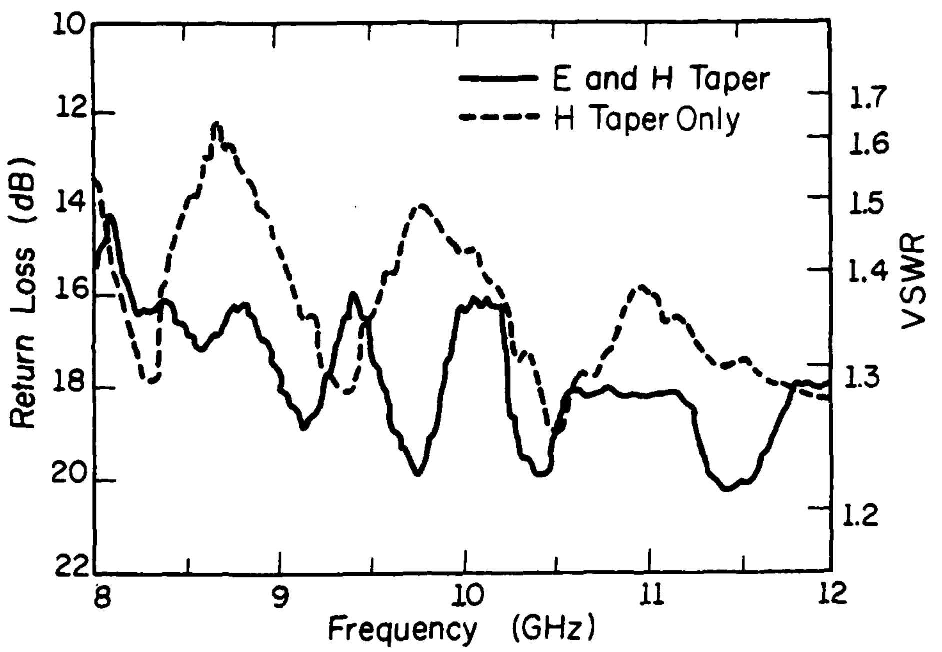

Fig. 8.5 Return loss and VSWR response for X-band transition with two types of dielectric taper.

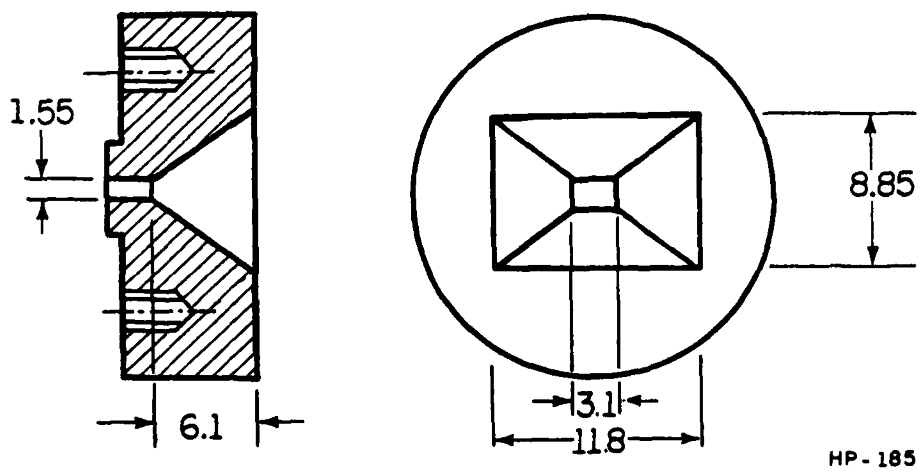

Fig. 8.6 Inside dimensions (mm) of the E-band launching horn.

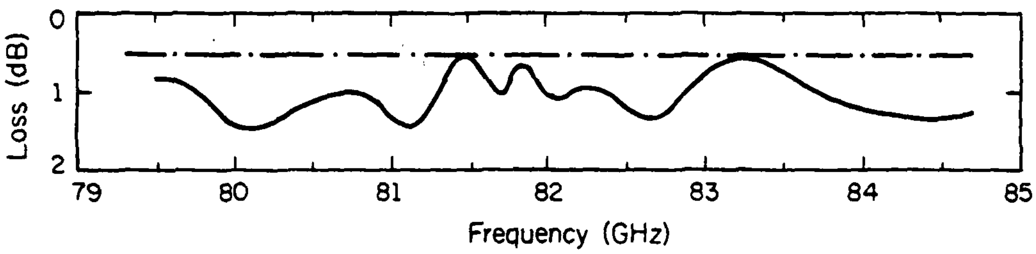

Fig. 8.7 Insertion Loss vs. frequency for the E-band transition and 86 mm long teflon guide: ——— Total insertion loss; —·— calculated loss for the dielectric only.

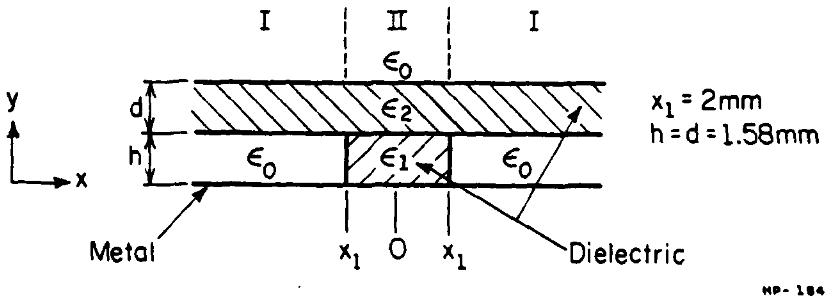

Fig. 8.8 Cross section of the inverted strip guide.

occurring at a few discrete frequencies.

The design of a transition between a metal and homogeneous inverted strip (HIS) guide, shown in Fig. 8.8, proved to be a much more difficult task than the one for the rectangular dielectric guide. Figures 8.9 through 8.11 show some of the various launching configurations which were investigated. We found that there is an optimum choice for the length I_L (see Figs. 8.9 and 8.10) that minimizes the reflection between the rectangular metal guide and the inverted strip guide when a tapered section is used for matching. On the other hand, for a horn-type transition shown in Fig. 8.11, the critical length is I_{TPL}. The length of the lower strip at the transition region (see Fig. 8.9) determined the higher-order mode content in that region with the fundamental mode predominating if the lower strip were sufficiently long. It was also determined that partial silvering of the two side faces significantly improves the performance of the launcher (see Fig. 8.12).

8.2.2 Multimoded Waveguides and Components

At higher frequencies, the fabrication of single-moded dielectric waveguides becomes increasingly difficult because the transverse dimensions of the waveguide become unmanageably small. Consequently, it is desirable to determine whether multimode waveguides and components can be employed in place of single-mode guides without compromising the performance of a system. We have determined that it is indeed possible by the theoretical and experimental investigation of a number of waveguide components, e.g., couplers and resonators. A typical test result is shown in Fig. 8.13.

8.2.3 Dielectric Antennas for Millimeter Waves

We have investigated two classes of dielectric antennas suitable for integration with dielectric waveguides. The first of these, which employs uniform or tapered dielectric rods of rectangular cross-section (see Fig. 8.14), radiates primarily in the longitudinal or end-fire direction. These will be referred to here as surface-wave antennas. The second type of antenna contains periodic discontinuities as shown in Fig. 8.15 and radiates at an angle dependent on the parameters of the

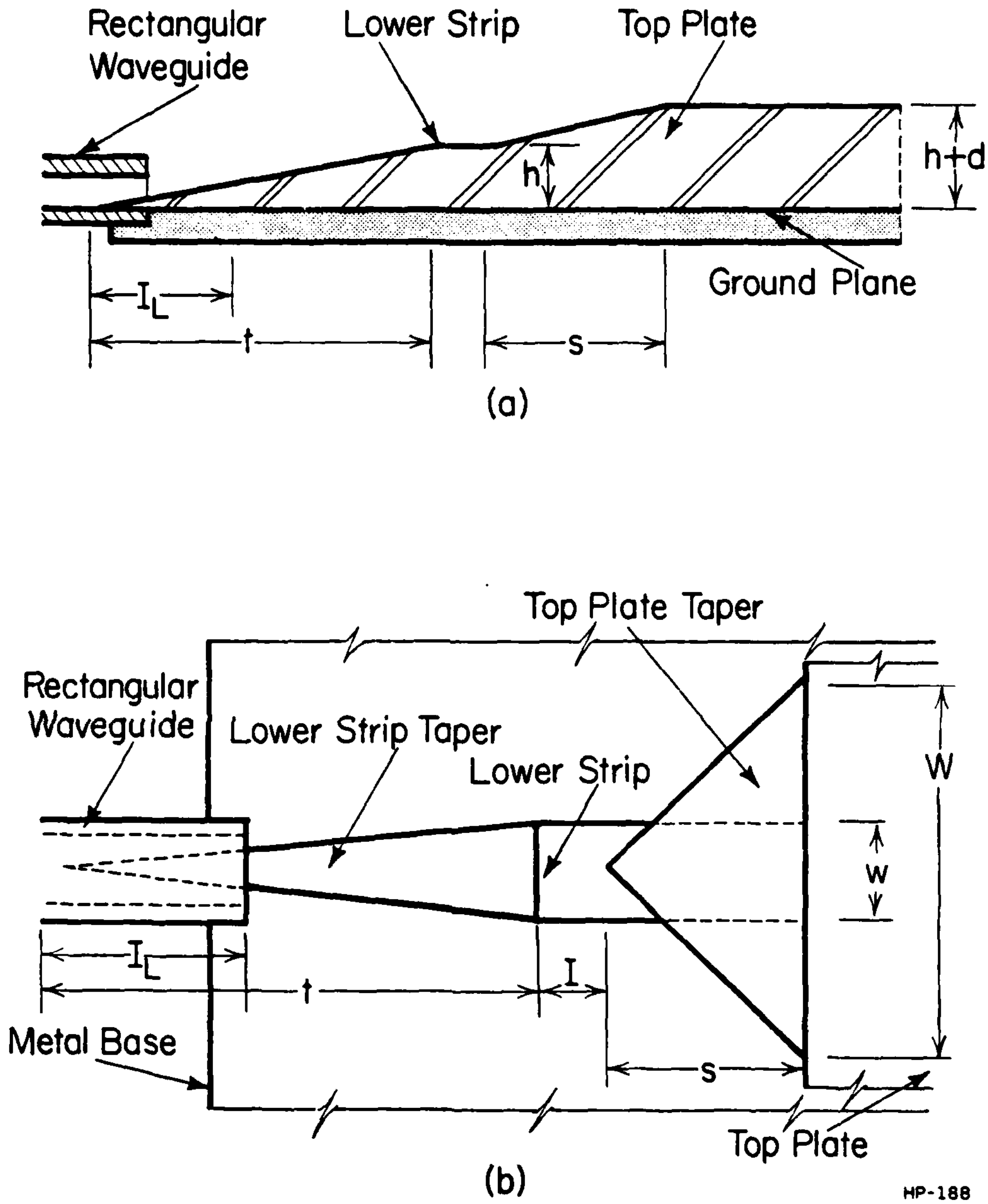

Fig. 8.9 Transition used for study.
(a) Cross section of the coupling arrangement.
(b) Top view of the coupling arrangement.

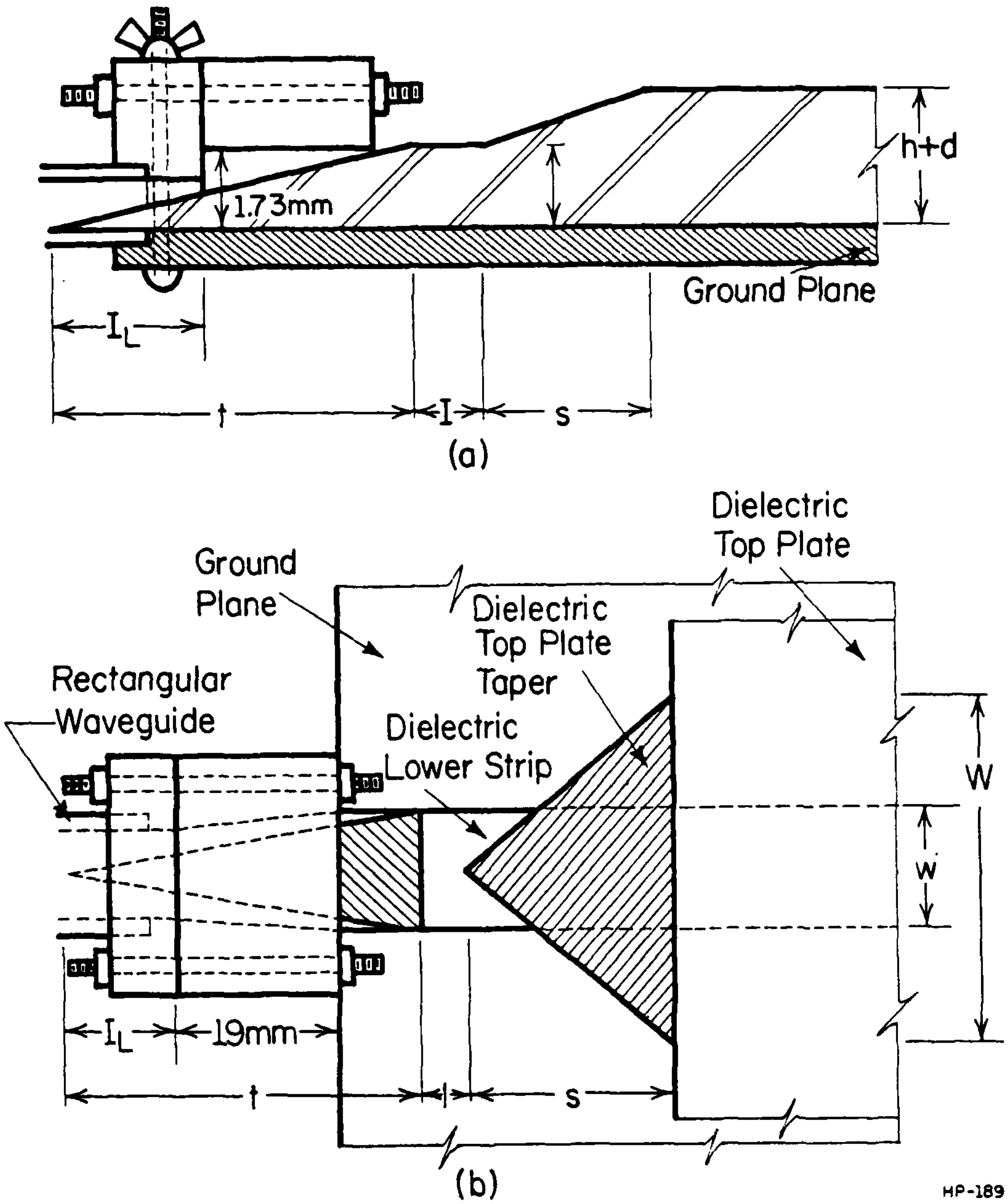

Fig. 8.10 Coupling arrangement with a horizontally flared horn.
(a) Cross section. (b) Top view.

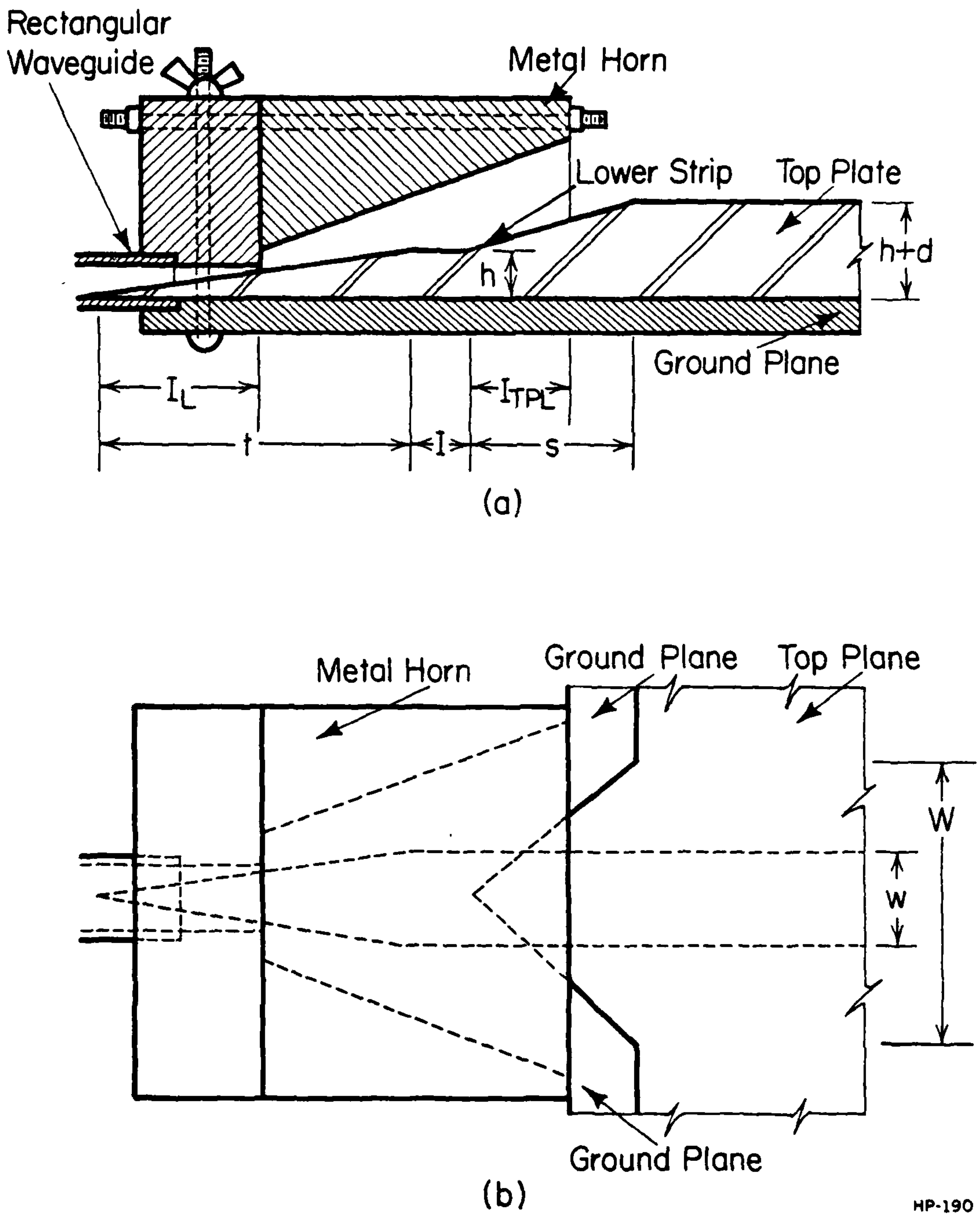

Fig. 8.11 Coupling arrangement with a horn flared in both planes.
(a) Cross section of the arrangement.
(b) Top view of the arrangement.

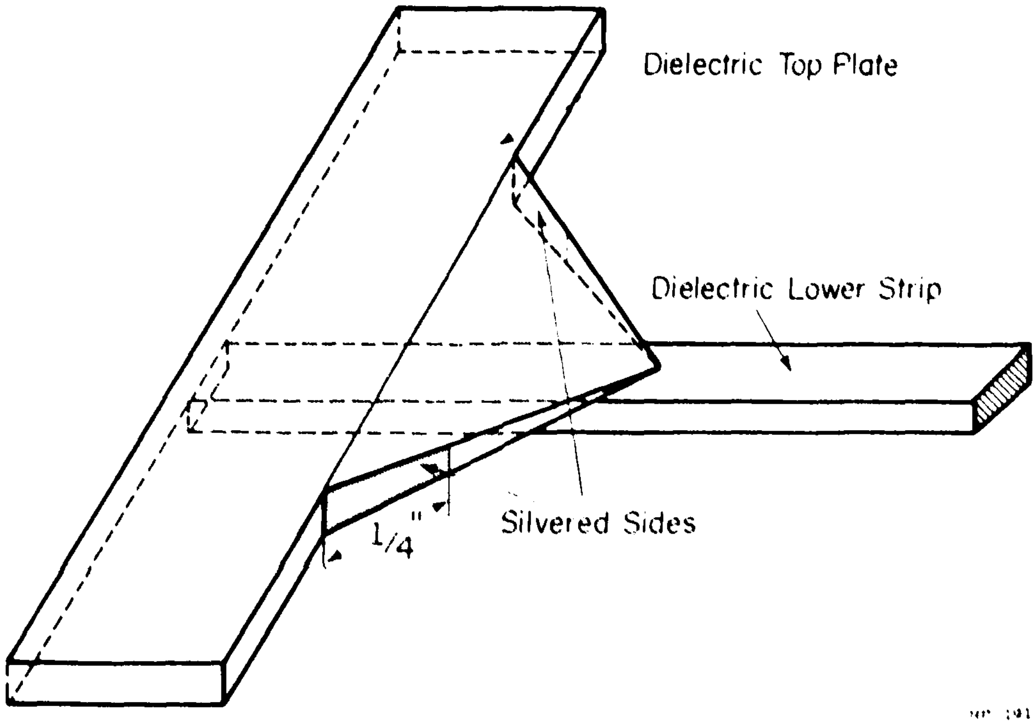

Fig. 8.12 A 3 dimensional view showing the partially silvered sides of the top-plate.

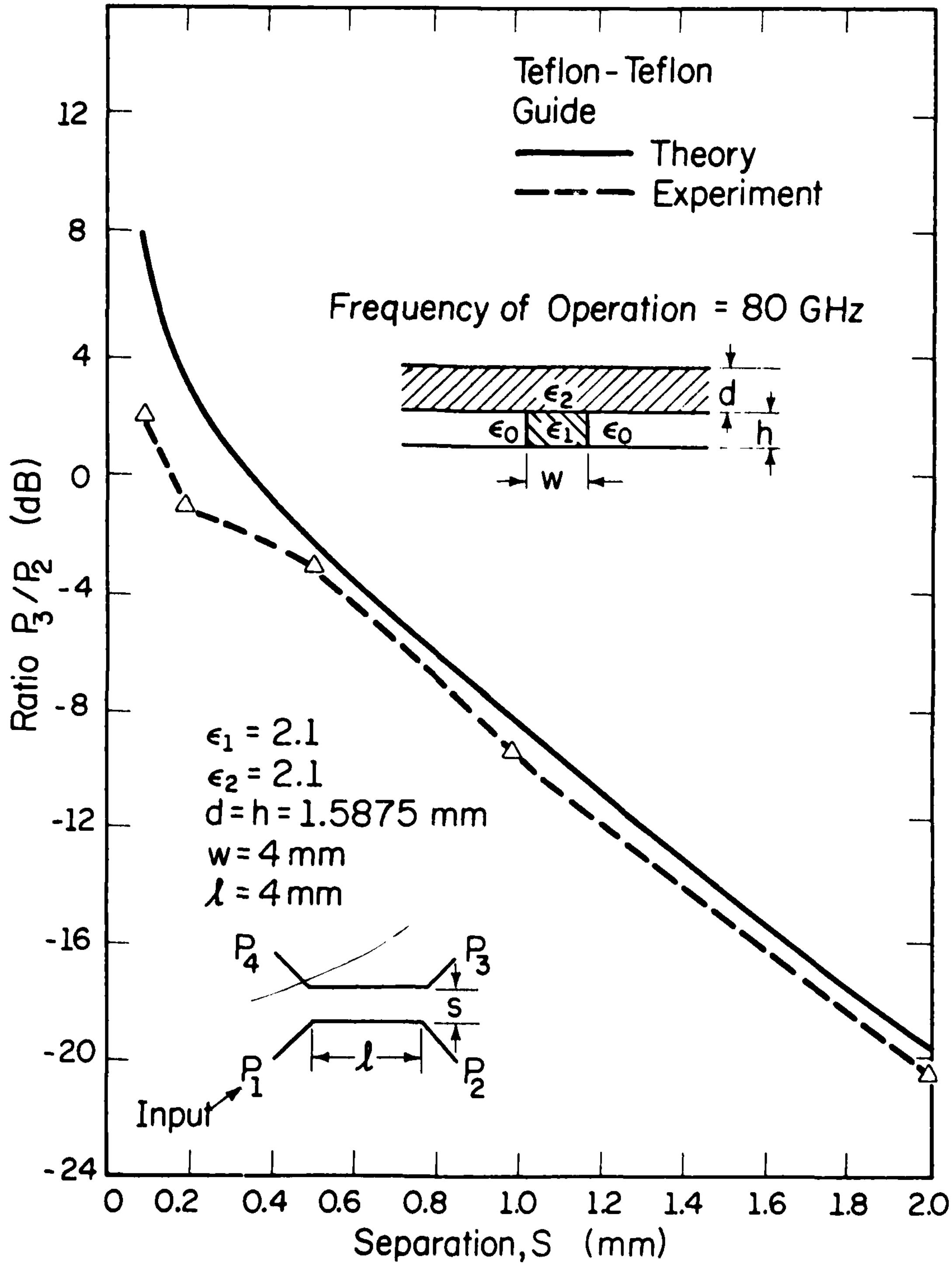

Fig. 8.13 Comparison of experimental and theoretical results of the HIS multimoded guide directional coupler.

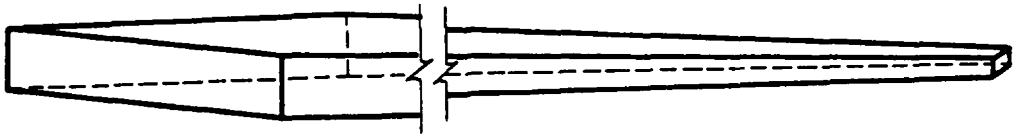

Fig. 8.14 A tapered rod surface-wave antenna.

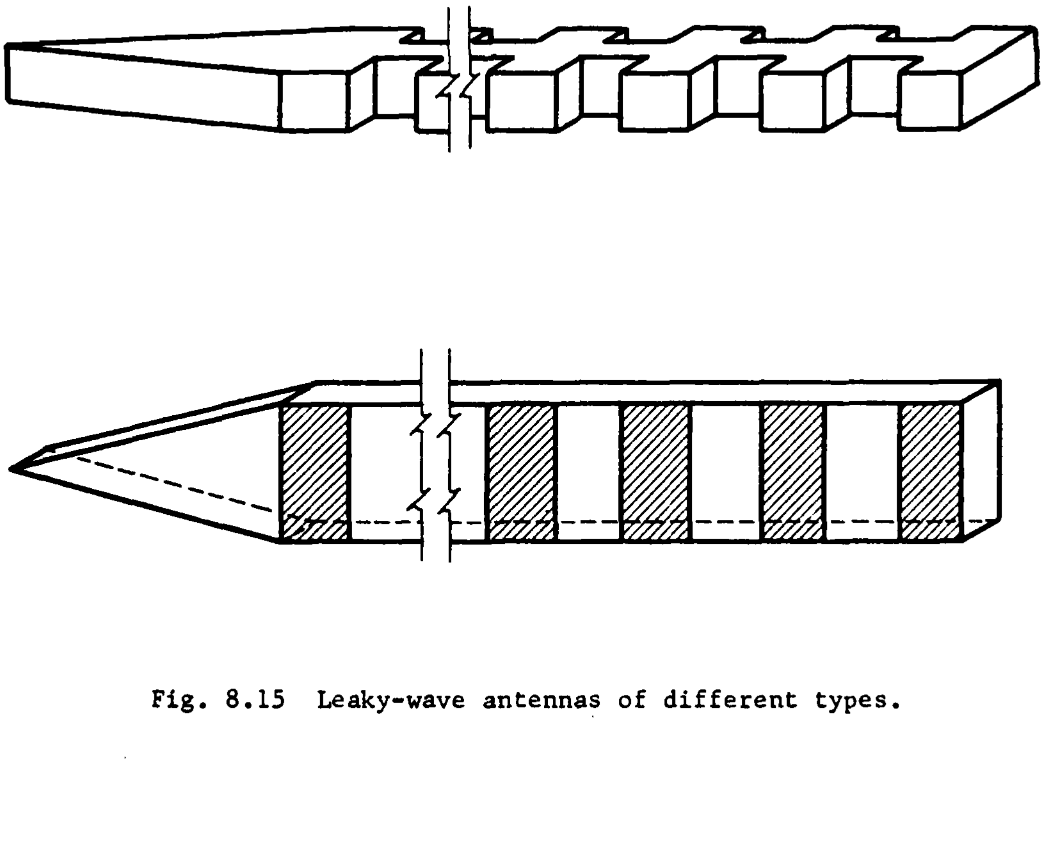

Fig. 8.15 Leaky-wave antennas of different types.

periodic discontinuity and the operating frequency. These antennas are frequency scannable about the broadside direction and are referred to here as leaky-wave antennas.

Both the surface- and leaky-wave antennas have been studied theoretically and experimentally. These studies have led to the determination of the optimum length of a surface-wave antenna from the point of view of antenna gain. We have also been able to design efficient leaky-wave antennas which radiate most of their energy along beam directions away from end-fire. The direction of radiation was accurately predicted on a theoretical basis.

8.2.4 Active Devices for Millimeter Waves

In investigating active devices for millimeter wave integrated circuits, a major emphasis was placed on extending the designs developed previously to 80GHz or above. A new configuration which was developed for the metal cavities housing IMPATT diodes, is shown in Fig. 8.16. In this design, a metal ribbon acts as the transition between the cavity housing the diode and the dielectric image guide. This oscillator design has been successfully operated at a number of frequencies and the effects of side-wall spacing, ribbon size, diode location, thickness of the dielectric, etc., on the frequency of oscillation and the output power were studied. Measurements were made for the conversion loss and the noise figure of an integrated receiver that used the oscillator design described above. The measurement setup which is shown in Fig. 8.17 yielded an insertion loss of 10-12 dB for the receiver at 30 GHz.

8.2.5 Active Probe

A new, active probe suitable for measuring near fields of integrated waveguides and circuits has been designed. A sketch of the device is shown in Fig. 8.18. The sensitivity of this probe is considerably superior to the passive probes we have previously used. The new design is presently undergoing extensive tests.

8.2.6 Theoretical Studies

The theoretical studies on millimeter-wave integrated circuits and antennas have proceeded in many directions. Variational and

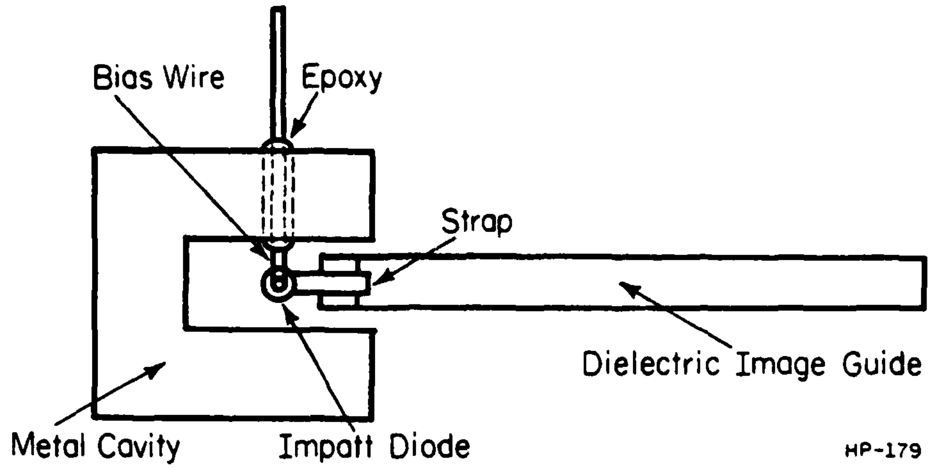

Fig. 8.16 New Impatt oscillator design.

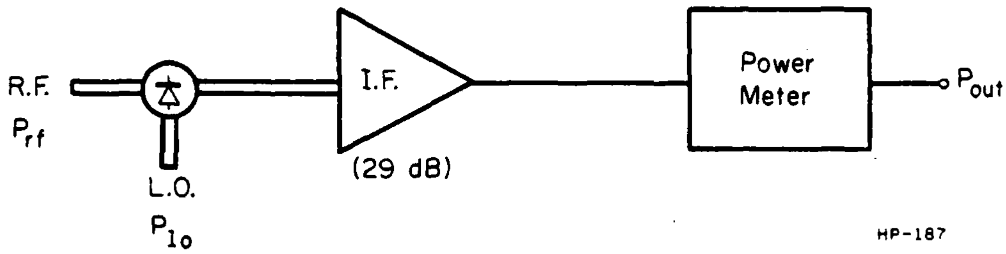

Fig. 8.17 Measurement of conversion loss.

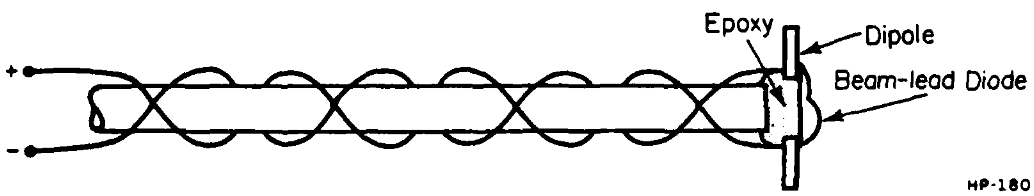

Fig. 8.18 Active probe.

mode-matching techniques for analyzing optical and quasi-optical guides of various cross-sections generated by planar facets have been developed. The theoretical results derived from the application of this method have been verified experimentally. Other theoretical studies included the analysis of coupled waveguides, transitions, multimoded guides and components, surface-wave antennas, and leaky-wave antennas.

8.2.7 Future Efforts

Future research efforts in the area of millimeter-wave integrated circuits will be directed toward investigating the unwanted radiation from bends and discontinuities in open dielectric waveguides and searching for means of preventing or reducing such radiation. This problem must be resolved before open dielectric waveguides can be used successfully in complete systems, e.g., receivers. During the next grant period, active devices will be built and tested in the 60-90 GHz range. The problem of arraying leaky-wave and surface antennas will be studied, and reflector-type antennas for millimeter waves will be investigated. The development of new, analytical methods for the investigation of radiation, scattering, and mode guiding properties of dielectric rods will be continued as will the design and testing of complete integrated circuit systems using dielectric waveguides.

8.3 Electromagnetic Radiation and Scattering*

During the past grant period the Fourier transform approach to solving electromagnetic radiation and scattering problems has been extensively utilized. The problem of radiation from sources located on curved surfaces with edges, e.g., a slot in a finite cylinder, has been studied and the radiation characteristics of the system have been derived using the concepts of the Spectral Theory of Diffraction. The spectral approach has also been applied to the investigation of another problem involving a finite cylindrical structure, viz., the scattering from struts

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contracts DAAG-29-78-C-0016 and N00014-79-C-0424, by the Office of Naval Research under Contract N00014-75-C-0293, and by the National Science Foundation under Grant ENG-76-08305.

in a reflector antenna.

New accuracy tests based on the transform approach and Lorentz reciprocity principle have been derived and applied to the problem of testing the accuracy of a number of high-frequency solutions generated by using asymptotic techniques, e.g., the GTD. Such accuracy tests play a very important role in establishing the confidence level in a given asymptotic solution and determining the useful range of application for such formulas.

In addition to the testing procedures, iterative methods for systematically improving a given asymptotic solution have also been developed. It has been found that in many instances the computation of diffraction coefficients based on GRD can take longer than generating an iterative solution which is usually more accurate and considerably simpler to evaluate.

Some of the new directions of research in this area include: (i) investigation of frequency selecting grating with applications to radome, reflector surfaces and far-infrared gratings; (ii) investigation of scattering by a dielectric cylinder whose dimensions are large compared to the wavelength, hence, its solution is unmanageable via conventional approaches; and (iii) application of the spectral approach to other problems of practical interest, e.g., the investigation of ultra-low sidelobe, reflector antennas.

The fundamental problem of deriving a convergence proof for the iterative procedures in the spectral domain will also be addressed.

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9.1 Statistical Properties of Ion Acoustic Turbulence

In the last progress report a method for measuring the one and two point probability distributions of density or potential fluctuations in a turbulent plasma were outlined. Measurements of the one point probability distribution P (φ) and the two time distribution P (φ_2, φ_1, t) have been conducted for a variety of parameters.

Figure 9.1 shows an example for the performance of the system. P (φ) was measured for purely electronic noise. The gaussian character is evident and can be followed over four orders of magnitude. Figure 9.2 shows a measurement in an actually turbulent plasma. The discharge current in this case was 5 amps at a pressure of 0.055, well in the unstable regime. Significant deviations from the gaussian behavior occur.

Measurements of P (φ_2, φ_1, t) result in a large amount of data which are best presented in reduced form. For the same conditions as in Fig. 9.2 we have measured P (φ_2, φ_1, t) for a fixed value of φ_1, namely 10 mV. The average value of φ_2, $<\varphi_2, \varphi_1, t>$ for a gaussian process is proportional to the correlation function R (t). This quantity is plotted in Fig. 9.3 together with the correlation function (dotted line) as computed from the measured spectrum of the unstable ion acoustic waves. The divergence of the two curves is again an indication for the non-gaussian character of the turbulent field. Systematic measurements to explore a wide range of plasma and instability parameters are in progress.

*This work was supported by the University of Illinois.

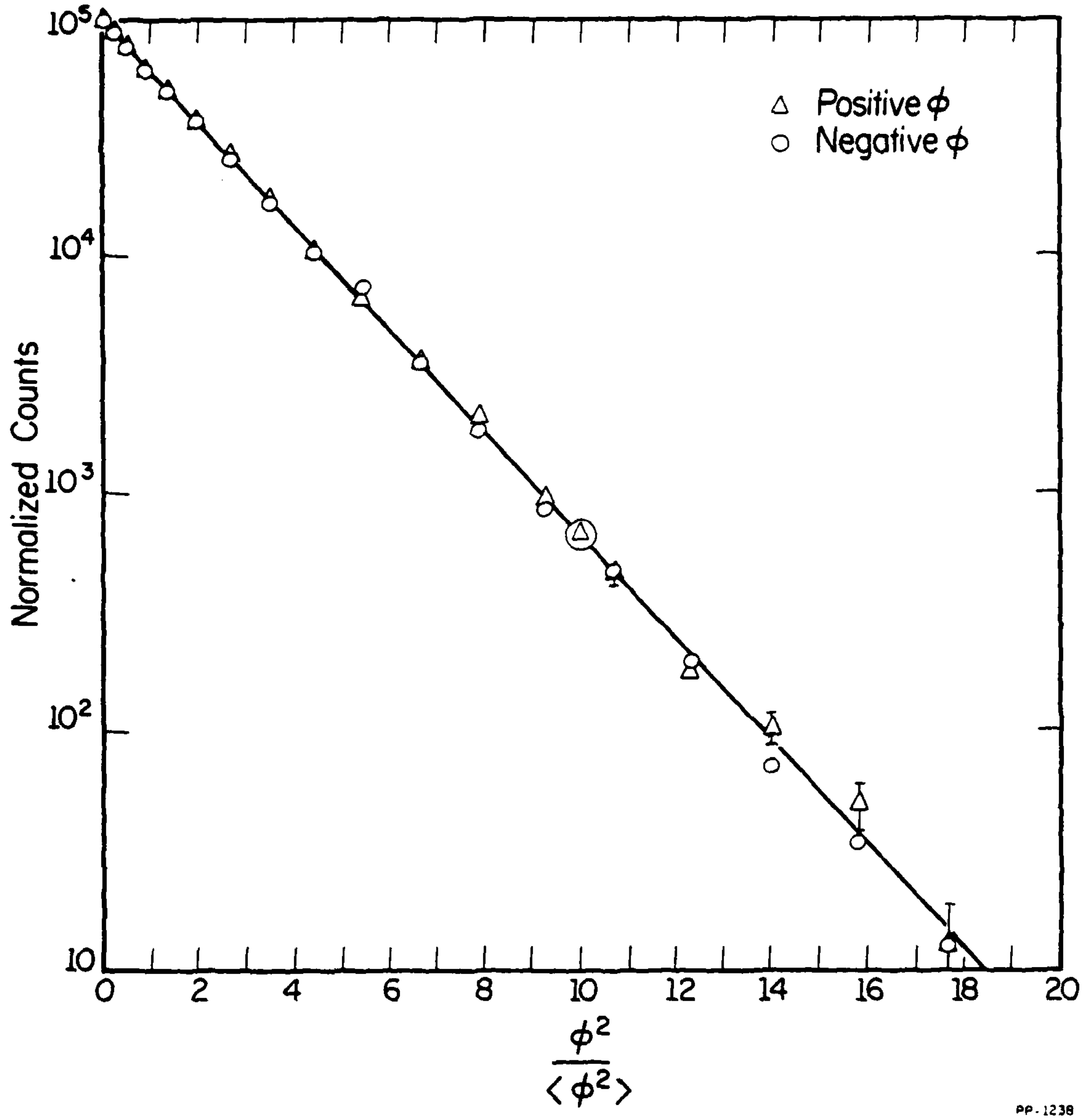

Fig. 9.1 Probability density of pure noise fluctuations.

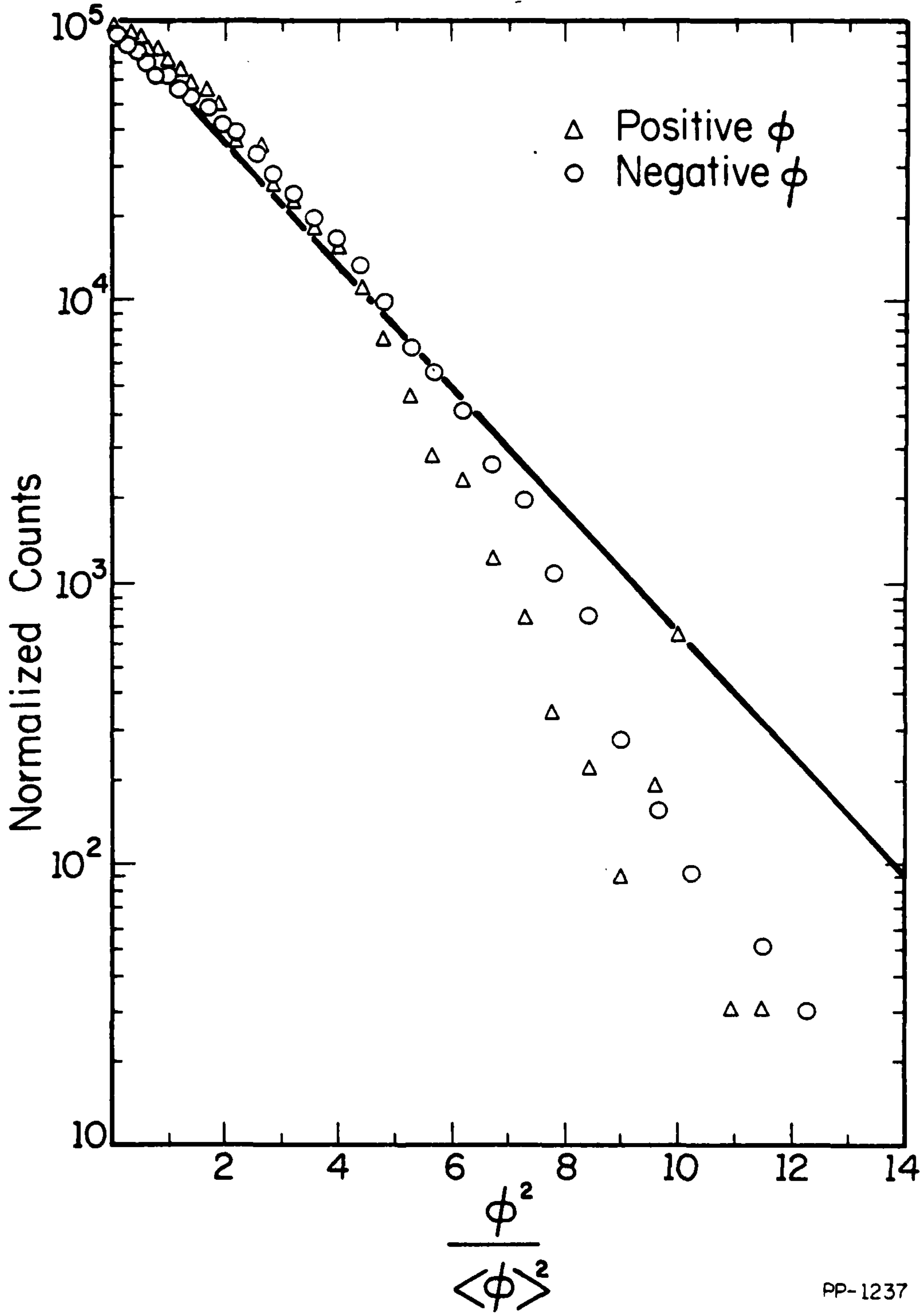

Fig. 9.2 Probability density of ion-acoustic turbulence.

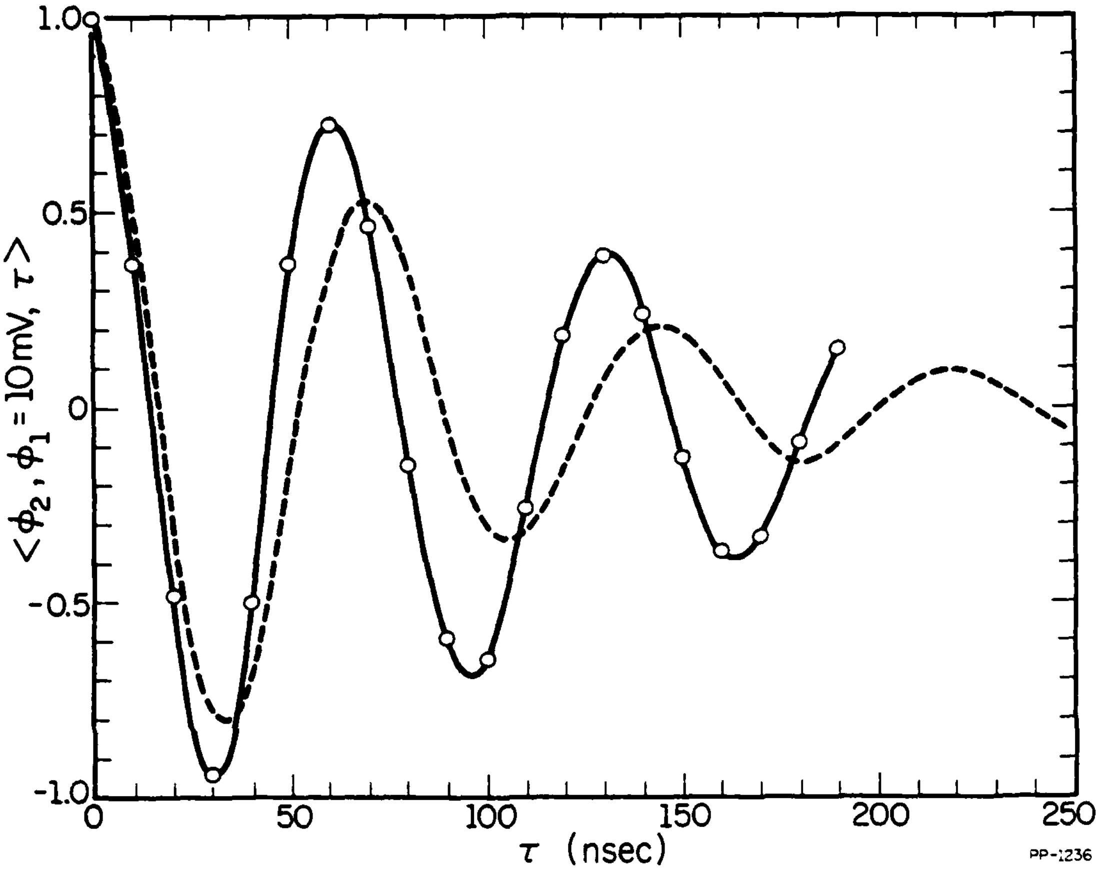

Fig. 9.3 Conditional two-time probability density (solid line) compared to the correlation function computed from the spectral density (dashed line).

9.2 Temporal Development of Ion Acoustic Turbulence

Measurements of the spatial growth rate of ion acoustic waves in a dc-discharge are complicated by the inhomogeneous plasma density and non-neutral character of the Faraday dark space in which the waves start to grow. It would, therefore, be desirable to conduct direct measurements of the temporal growth rate. This can in principle be accomplished by switching on the discharge current from a stable to an unstable value on a time scale that is fast compared to the growth rate of the ion acoustic waves. The difficulty with this scheme is due to the fact that the ionization time necessary to establish new steady state conditions is much longer than the inverse of the growth rate. We have devised a method by which this difficulty can be circumvented. It is accomplished by switching the discharge current rapidly below the threshhold of the instability and switching it on again a few microseconds later. The unstable waves decay rapidly be collisional damping, the plasma density, however, decays much more slowly by ambipolar diffusion. Conditions can, therefore, be achieved in which only the drift velocity is suddenly increased without changing the electron density. Switching is actually accomplished with a IR-423 transistor, used to bypass up to several amperes discharge current in a time of the order of 0.1μ sec. Problems arise with conventional probe diagnostics because the plasma potential changes rapidly. A bootstrap scheme designed to eliminate the effect of potential fluctuations is presently being tested.

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10.1 Introduction

Rarefied gas dynamics deals with non-equilibrium gas flow problems in which microscopic treatment according to kinetic theory is necessary to determine the effect of intermolecular collisions and gas surface interactions on both the microscopic and macroscopic gas flow properties. Such rarefied gas flow problems occur in aerodynamics, electronics, aeronomy, environmental fluid dynamics, and other related fields.

The aim of this research program is to develop numerical methods to solve a wide range of problems under conditions far from and near thermal equilibrium. A Monte Carlo method has been developed at Coordinated Science Laboratory [1] to solve directly the Boltzmann equation and has been used by the Coordinated Science Laboratory Boltzmann group to solve the Boltzmann equation for several rarefied gas flow problems under a wide range of equilibrium and boundary conditions [2-7]. The solutions we have obtained yielded detailed microscopic and macroscopic non-equilibrium properties, most of which have never been treated and studied before. We have also studied numerical solution of other kinetic equations and other numerical methods to solve rarefied gas flow problems, including the direct simulation technique.

10.2 Study of Evaporation-Condensation Problems*

Nonlinear evaporation-condensation problems are encountered in such diversified areas as upper atmosphere meteorology, the cooling of

*This work was supported by NATO Research Grant 1075 and by the University of Illinois.

nuclear reactors, design of space experiments, petrochemical engineering, vacuum technology, and the interaction of high power laser radiation with metal surfaces. The treatment of practical evaporation-condensation problems requires the consideration of heat conduction in the dense phase, kinetics of phase transition and kinetics of vapor in gaseous phase. Since each problem has its own peculiar conditions in the dense phase and at the interphase boundary, it would be appropriate to study first the vapor kinetics problem with a simple set of boundary conditions as shown in Fig. 10.1. The vapor kinetics problem is characterized by the non-equilibrium vapor condition at the interphase boundary. At the interphase, there are two distinct groups of vapor molecules, one emitting from the boundary and the other impinging the boundary and the vapor is, therefore, not in equilibrium condition. The vapor relaxes to the equilibrium condition in a distance of the order of one mean free path. The relaxation region in which the vapor undergoes large changes in properties is referred to as the Knudsen layer. The treatment of flow in it requires the use of kinetic theory. The use of kinetic theory approach highlights the fact that the non-equilibrium motion in the Knudsen layer has direct influence on the evaporating and condensing flow parameters such as the molecular transports and the edge conditions, and, thus, on the ensuing flow field.

We have undertaken a joint research effort with Ytrehus of the University of Trodheim of Norway and Wendt of Von Karman Institute of Fluid Mechanics of Belgium to study these problems under a NATO Research Grant. Under this joint effort, we have successfully simulated the half-space evaporation-condensation problem by solving the Boltzmann as well as the Krook equations for a two-wall emitting and absorbing problem [8] first suggested to us by Cheremissine and studied by us [6] in detail. The simulated problem is shown schematically in Fig. 10.2. The success of our attempt to solve directly the Boltzmann equation for this half-space problem is of basic interest and could lead to similar attempts to study the half-space problems by using the accurate kinetic theory approach.

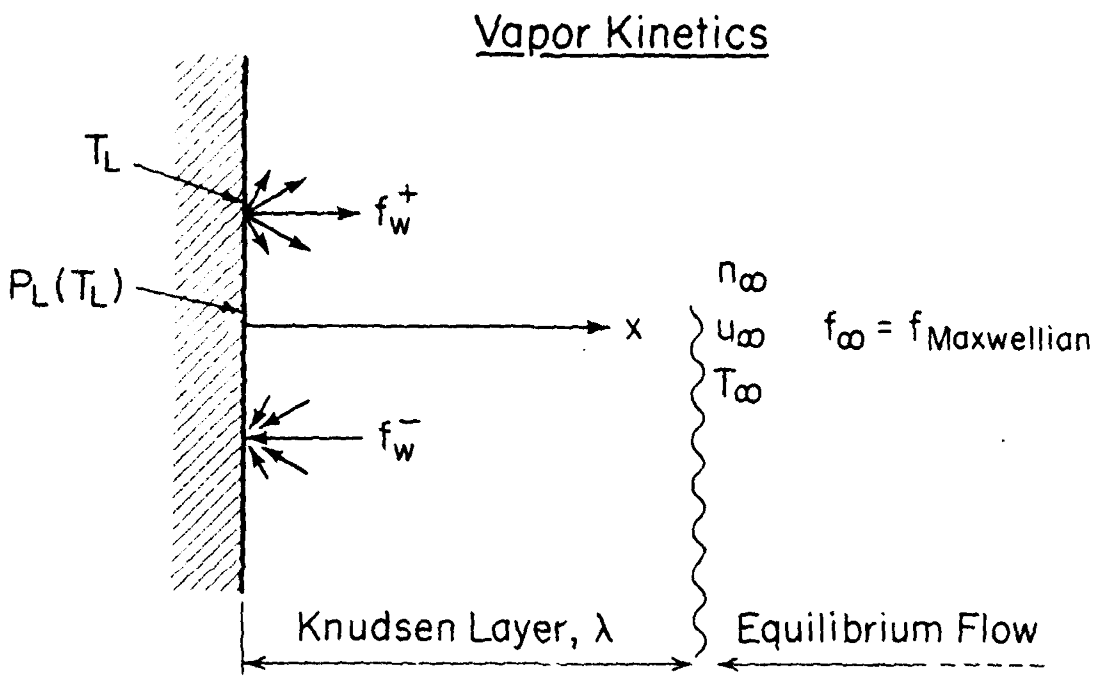

Fig. 10.1 Kinetics of the vapor motion near the interphase. Knudsen layer. λ = mean free path.

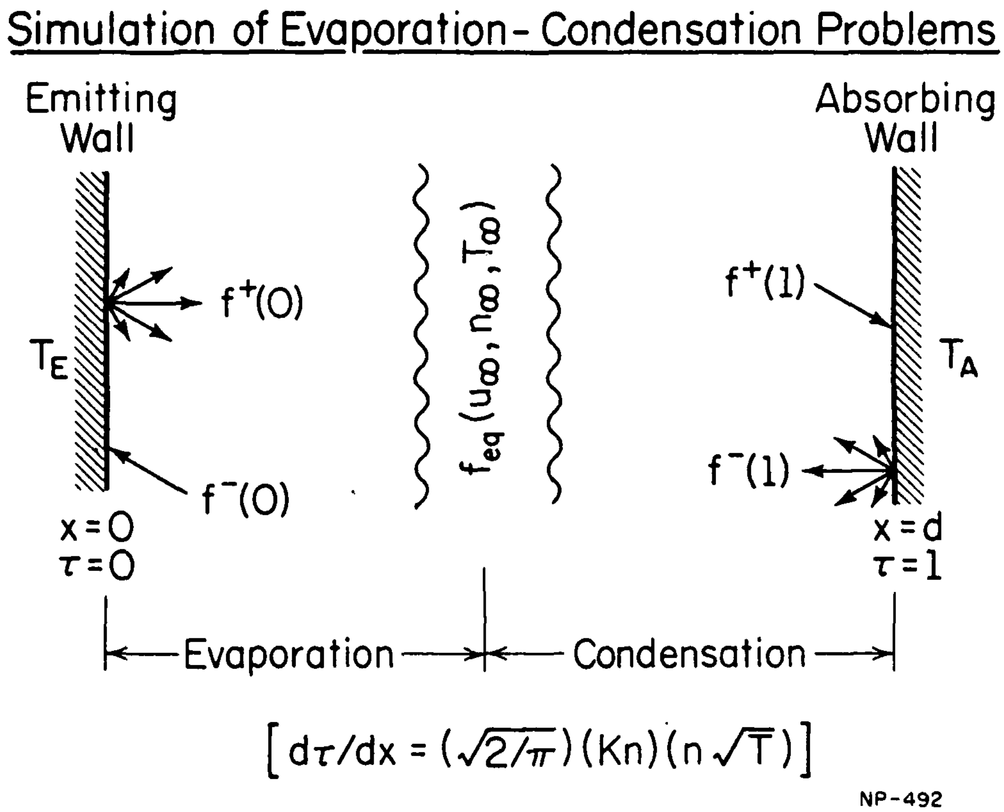

Fig. 10.2 Numerical simulation of half-space evaporation and condensation problems.

The solutions obtained establish the validity of Ytrehus' simple kinetic theory approach to make parmetric studies of evaporation problems and the conditions under which theoretical calculations can be correlated with others as well as with experimental results. The results obtained by us and Ytrehus were presented at the 10th Rarefied Gas Dynamics Symposium, Aspen, Colorado in July, 1976 and were published [9,10]. We have made further numerical studies of the Krook solutions for large mass rate in order to study the simulation near the downstream limiting Mach number of 1. These results were presented at the 11th Rarefied Gas Dynamics Symposium, Cannes, France in July, 1978 [11].

We have been undertaking the task of extending our study to the condensation problem. As shown in Fig. 10.3, the condensation problem differs from the evaporation problem in the edge conditions at the interphase. For the evaporation problem, the evaporating molecules are characterized by T_L, temperature of the liquid, and P_L, the saturation pressure; however, the flow parameters of the backscattering molecules ($\dot{m}_b$) are unknown. For the condensation problem, the flow parameters of the condensing molecules ($\dot{m}_b$) are unknown. According to the method of Ytrehus, the edge conditions as functions of P_L/P_∞ can be calculated for the two problems and are shown in Fig. 10.4.

Our research has followed the following plans of study:

(1) Solve the Boltzmann equation, the basic equation in kinetic theory, for conceptually simple but physically as significant evaporation and condensation problems.

(2) Study the non-equilibrium behavior of the vapor motion in the Knudsen layer by analyzing the macroscopic as well as the microscopic properties obtained from our Boltzmann solutions.

(3) Study the flow parameters of the evaporating and condensing flows, e.g., the edge conditions of the Knudsen layer.

(4) Compare our Boltzmann results with those of simple kinetic theory approaches in order to establish the validity of these approaches.

(5) Apply these approaches to problems of more complex boundary and flow conditions.

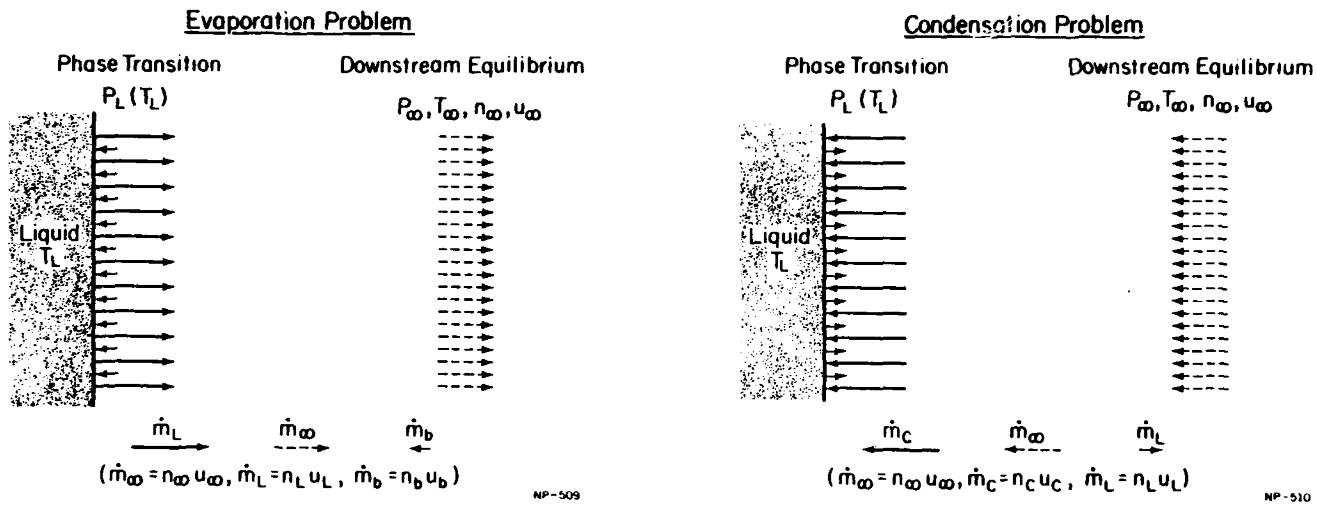

Fig. 10.3 Mass fluxes in evaporating and condensing flows.

<u>Evaporating flow</u>: $\dot{m}_L$ = evaporation flux.
$\dot{m}_b$ = backscattering flux.
$\dot{m}_\infty$ = downstream flux (outgoing).

<u>Condensing flow</u>: $\dot{m}_L$ = reflecting flux.
$\dot{m}_c$ = condensing flux.
$\dot{m}_\infty$ = downstream flux (incoming).

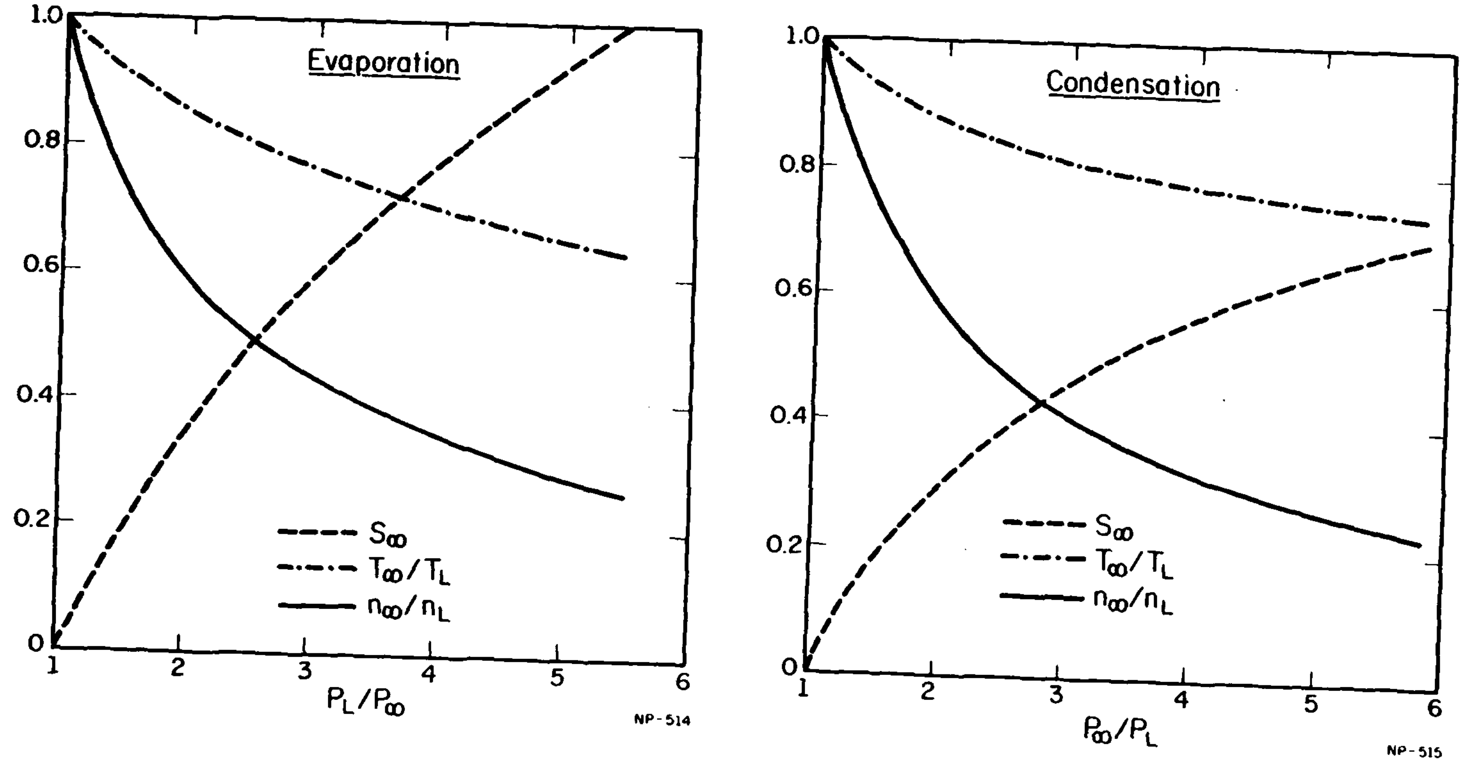

Fig. 10.4 Downstream speed ratio S_∞, temperature ratio T_∞/T_L and density ratio n_∞/n_L as functions of the pressure ratio P_L/P_∞.

We plan to study further the evaporation and the condensation problems by considering more complex flow and boundary conditions. For the evaporation problem, we shall first consider the effect of cross flow at the outer edge of Knudsen layer. We believe a simple approach could be developed to evaluate the edge conditions of the Knudsen layer. This approach would be useful in studying the factors affecting the evaporation and in making calculations of evaporating flow field. We shall also consider the effect of internal energy transfer in the dense phase. In this study, we plan to develop a scheme to implement such a boundary condition in our Boltzmann method as well as the simplified approach. We shall then study the difference in the non-equilibrium vapor motion in the Knudsen layer as well as the edge conditions due to the change in boundary conditions.

The non-equilibrium vapor near a condensing surface differs from that near an evaporating surface because of the difference in edge condition at the interphase boundary. Our Boltzmann solutions yield distinct non-equilibrium behavior in the Knudsen layer of condensing vapor. For example, the temperature gradient becomes negative near the interphase under certain conditions. The condensing phenomenon seems to be more complex. One of our tasks is to develop a simple approach, similar to that for the evaporation, to correlate the edge conditions of the Knudsen layer for the condensing flow. The accuracy of this approach will be examined by comparing the results with those obtained from our Boltzmann solutions. This approach would be useful in calculating fluxes through the Knudsen layer and, therefore, the condensing flow field.

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11.1 Introduction

The objective of this research program is to solve numerically the basic inviscid and viscous gas dynamic equations for complex problems. We have studied the application of finite element, finite difference and hybrid methods to problems of complex geometries and boundary conditions. We shall report our research efforts on the numerical solution of non-linear free surface wave problems.

11.2 Study of Free Surface Wave Problems*

There are three major problems associated with the numerical solution of free surface problems: to accommodate accurately the free surface geometry, to satisfy the boundary condition uniformly over the free surface and to treat the radiation boundary condition. Computational methods have been developed to deal with these problems and have been used to solve several free surface problems. However, computational difficulties are encountered in the application of these methods to problems under certain conditions. On the other hand, each of these methods has advantages over the others in the solution of a particular class of problems. Our research on the computational methods using the Eulerian approach [1-5] has led to several conclusions concerning further studies:

(1) The time-dependent approach can be used to solve the initial phase of development of free surface flows. In computations involving longer times, study has to be made to reduce the accumulation of diffusive error.

*This work was supported by the National Science Foundation under Grant ENG 77-20436.

(2) The finite element method can be used to reduce the interpolation error; however, the implementation of this method is more complex. In order to increase computation efficiency for complex problems, we should consider a hybrid method that combines the finite element and finite difference grid systems.

(3) On the basis of considerations of error accumulation, the steady state approach is more favorable. However, the treatment of the open boundary condition should be studied.

11.2.1 Further Application of our Computational Schemes

(1) Elliptic Cylinder

We have obtained the solution of a submerged elliptic cylinder of a larger thickness ratio of 0.8 and $Fr = 1/\sqrt{\pi}$. The wave profile development is shown in Fig. 11.1. Filtering was used to control the numerical error after $t = 0.9$.

(2) Hydrofoil

We have initiated an effort to implement the Kutta condition for the hydrofoil problem. Figure 11.2 shows the finite element mesh system for an unsymmetrical hydrofoil. We have revised our method so that we can use it to solve the unsymmetrical hydrofoil problem with accurate implementation of the Kutta condition.

The revision of our method includes the refinement of a mesh system near the free surface. A more accurate solution was obtained for the symmetrical airfoil problem using this revised method and the wave profile for $t = 1$ is shown in Fig. 11.3.

11.2.2 Development of a Hybrid Scheme

The objective is to develop a scheme to solve the free surface wave problem using a finite computational domain. The downstream boundary is set close to the disturbance. We wish to find a scheme to implement the condition at this boundary so that it can be used together with our methods to compute the flow development in the domain.

We have developed a hybrid method by using a finite computational

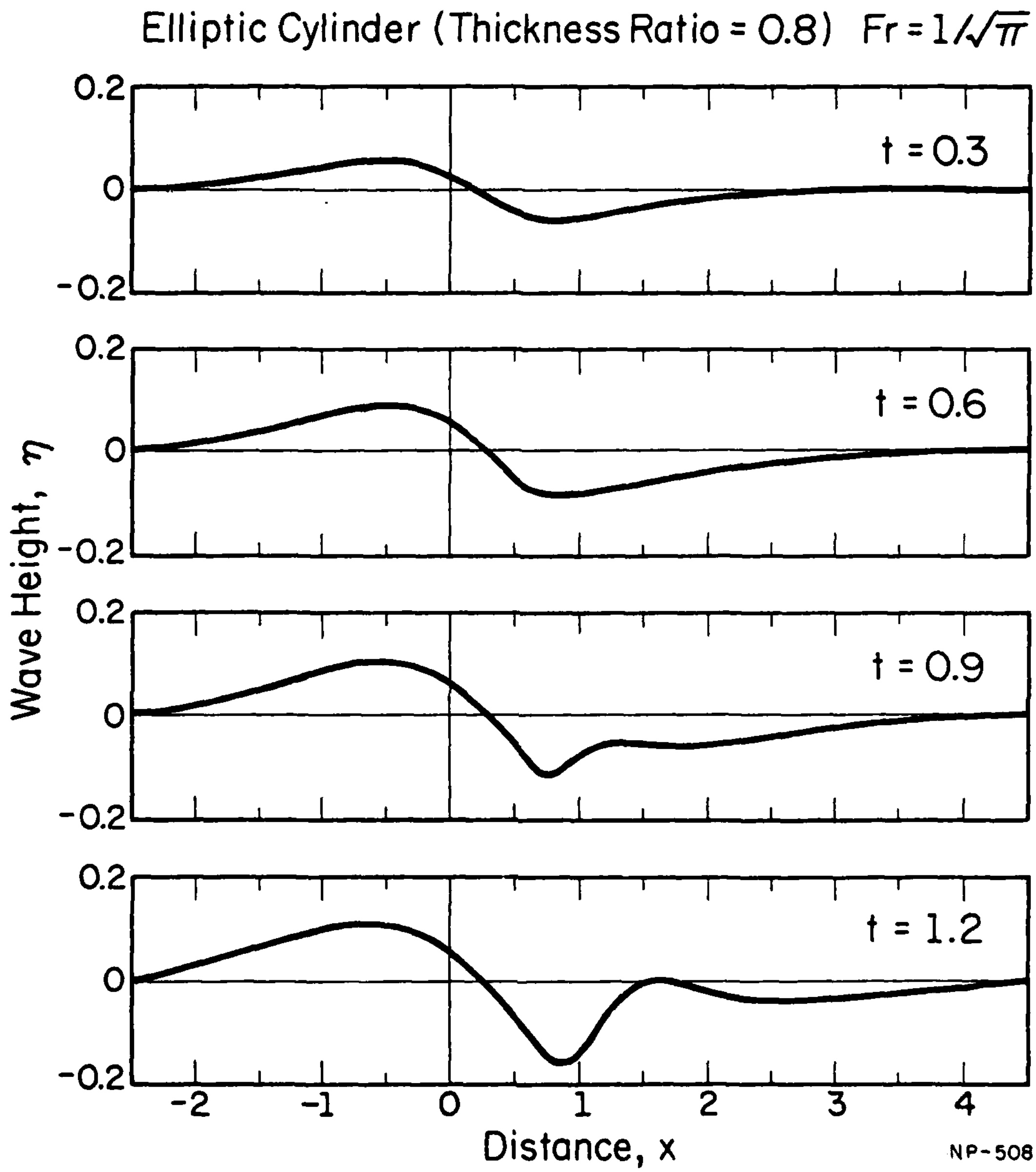

Fig. 11.1 Wave profiles at $t = 0.3, 0.6, 0.9$, and 1.2. Elliptic cylinder (thickness ratio = 0.8). $Fr = 1/\sqrt{\pi}$

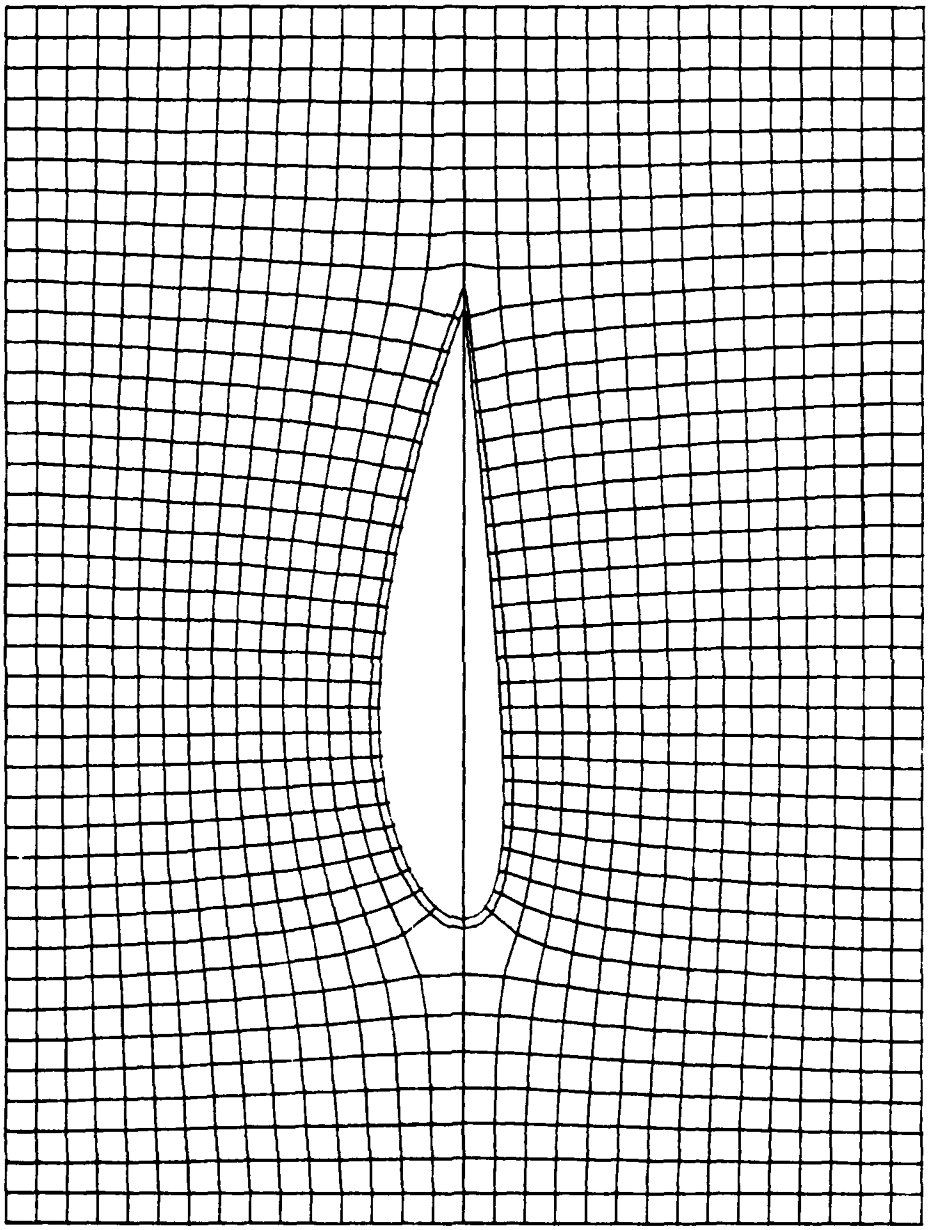

Fig. 11.2 Mesh system for an unsymmetrical hydrofoil.

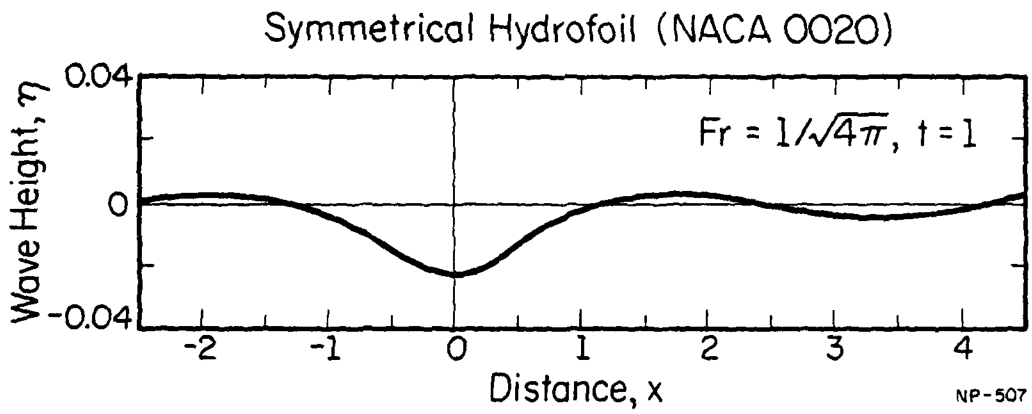

Fig. 11.3 Wave profile at t = 1. Symmetrical hydrofoil (NACA 0020). $Fr = 1/\sqrt{4\pi}$.

domain to implement our numerical schemes. In this method, we apply the Orlanski scheme using Chan's algorithm at the downstream boundary [6].

We conducted a series of numerical experiments by applying the hybrid method to the pressure distribution problem with $Fr = 1/\sqrt{2\pi}$. The downstream boundary is set at a distance of 1.5 from the center of the pressure distribution. The resulting wave profile at $t = 1$ is shown in Fig. 11.4. We observe that the $2\ \Delta x$ wave which starts at $t = 0.8$ has already spread a large distance upstream. In fact, this wave keeps growing and eventually causes the calculation to stop at $t = 3$.

We have developed a method to eliminate the $2\ \Delta x$ waves by filtering. This method is so designed that it does not impair the accuracy of wave calculations. One of the resulting waves is shown in Fig. 11.5. The filtering eliminates the $2\ \Delta x$ waves that appear downstream ($t = 1$). Furthermore, the results with filtering are in agreement with those obtained with expanding domain (i.e., without boundary effect.) Figure 11.6 shows the comparison of wave drag for the filter case with that of the unfiltered result. The result with filtering is also in agreement with that obtained by using an expanding domain.

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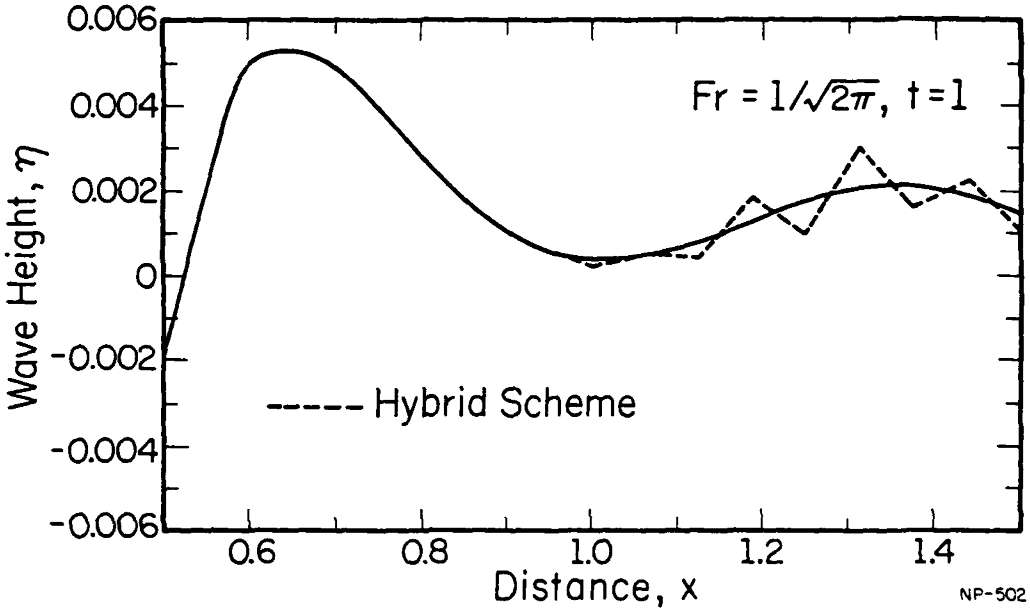

Fig. 11.4 Development of $2(\Delta x)$ wave near the downstream boundary due to the implementation of radiation boundary condition used in the hybrid scheme. Wave profile shown is for the pressure distribution problem. $Fr = 1/\sqrt{2\pi}$. $t = 1$

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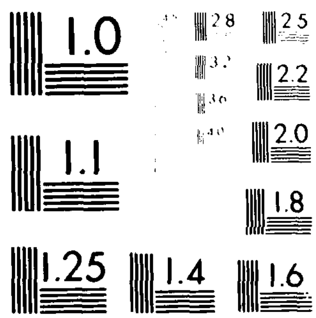

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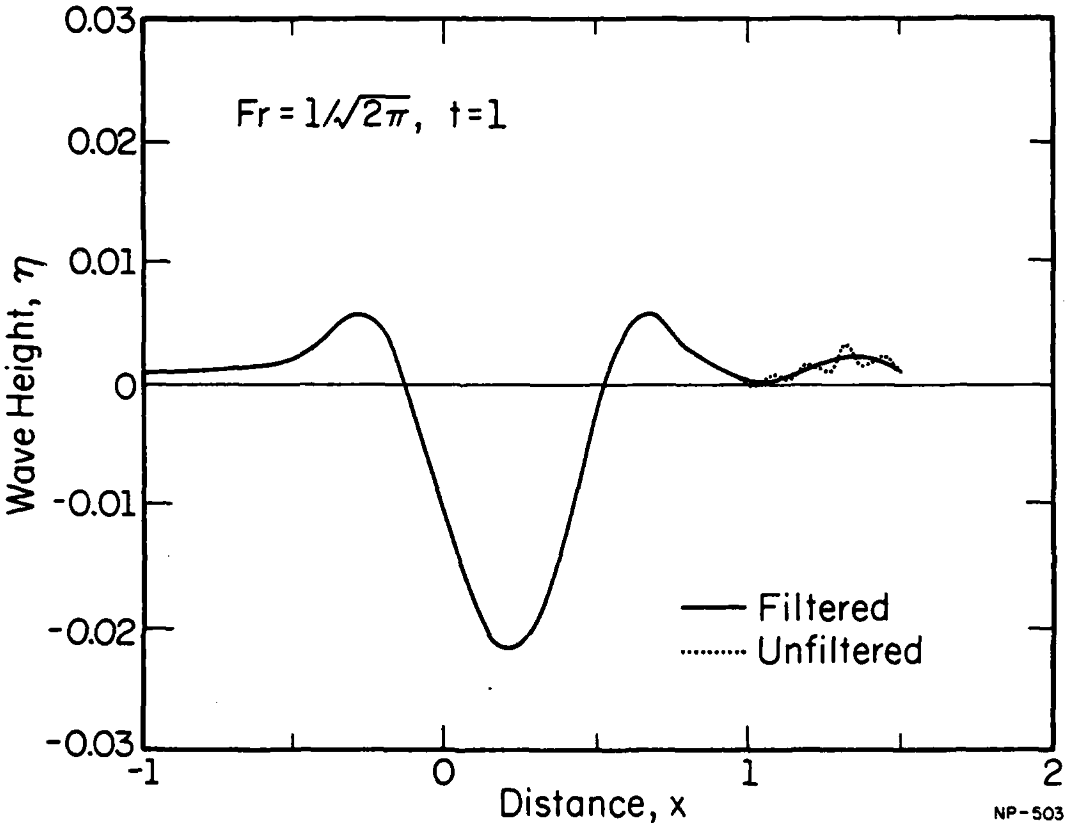

Fig. 11.5 Filtering the 2(Δx) wave near the downstream boundary. Wave profile. The pressure distribution problem $Fr = 1/\sqrt{2\pi}$. $t = 1$

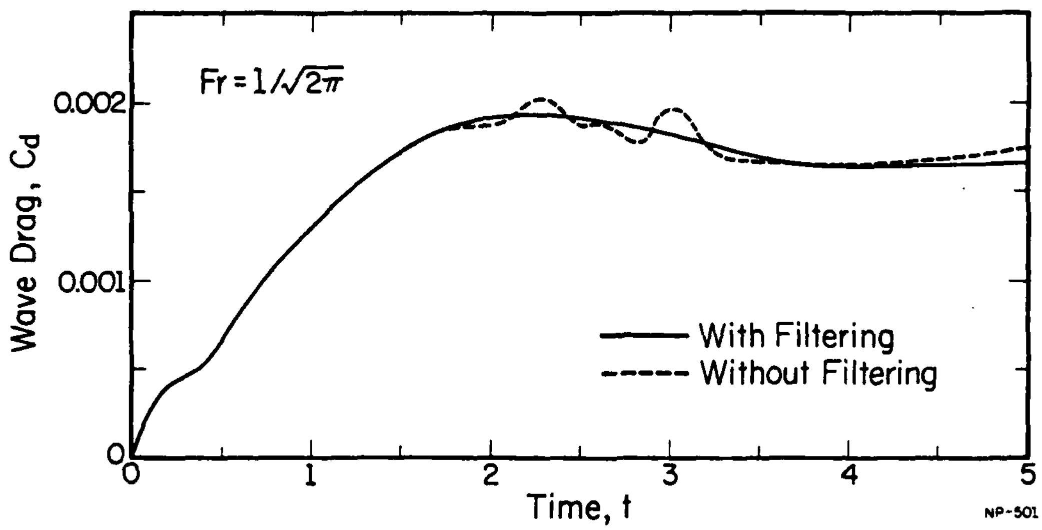

Fig. 11.6 Elimination of error in wave drag calculation by filtering. The pressure distribution problem. $Fr = 1/\sqrt{2\pi}$.

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12.1 Fault-Tolerant Distributed Systems

Research in this area includes the design, modeling and performance evaluation of loosely coupled, fault-tolerant distributed systems as well as techniques to test the units of a system in order to detect faulty units.

12.1.1 Modeling and Design of Systems

A new algorithm has been found to calculate the probability of communication between a pair of nodes in a network [1]. A program has been written in SAIL, and the algorithm has been found to be much faster than existing ones. An analytical model has been developed to study shared-resource multiprocessor systems operating under a graceful degradation policy. A new measure of performance based on both the availability and performance of the system was defined and system design guidelines have been found.

A broad study is being made of load sharing and load redistribution in a distributed system; a model has been developed to determine the minimal cost assignment of tasks to processors for various parameters, given a program and an n-processor distributed system. Work is also in progress to analytically model the performance of various techniques to manage queues of failed processors in a distributed system.

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12.1.2 Test Generation for Microprocessors

Classical methods of test generation are not suitable for microprocessors because of the large number of gates and flip-flops with low controllability and observability on a chip, and because such a description of a microprocessor is usually not available to the user. Very encouraging results have been obtained in the area of test generation at a functional level [2,3,4]. A general graph-theoretic model for microprocessors was developed at the register transfer level. Any microprocessor can be easily modeled using information only about the instruction set and the functions performed by it. A fault model was developed on a functional level quite independent of the implementation details. The test generation procedures then take the microprocessor organization and the instruction set as parameters and generate tests to detect all the faults in the fault model. Actual simulation has verified the usefulness of the approach.

12.2 Computer Architecture

12.2.1 Fixed-Cycle Resources for a Pipelined Processor

This research has centered on the performance of functional resources that are used by a single multiple-stream pipelined processor. Such resources include arithmetic functional units and the modules that compose an interleaved memory. The functional requirement of such resources is that they perform some operation and resynchronize their results with the associated stream in the pipelined processor.

In some instances, a replicated or pipelined resource can be used to achieve the required performance. However, in this research a simple non-pipelined unit with a fixed cycle time is being investigated as a lower cost alternative. This resource is characterized by a cycle time, c, and a deadline, d, which if missed results in a penalty of one non-compute pass through the pipeline.

The performance of this type of resource for various resource scheduling techniques has been determined through the use of Markov modeling and some model reduction methods. It is shown that very high performance can be obtained when effective use is made of the available deadlines. An extension to this model allows the consideration of resources with

access times not equal to their cycle times.

Various applications for this type of resource are examined including an implementation of a cost-effective control store which attains high performance through the use of interleaving. Such an organization is most directly relevant to multiple stream processors, which execute several programs simultaneously, yet require only a single microprogram store with our implementation. Additional design constraints are developed for the specification of branch resolution times and for the addition of dummy segments to enhance overall system performance. The cost design trade-offs for interleaved memories with deadlines are also examined. In addition, the performance of parallel processor-memory configurations is contrasted to systems with time-multiplexed requests and deadlines with the resultant elimination of the expensive crossbar switch. Formal mechanisms for evaluating performance with all of the above considerations have been developed.

This research is reported in part in [5] and in full in [6]. This work is being extended to model more general cases. This extension is discussed in section 12.4.1 below.

12.2.2 Comparative Analysis of Parallel Computer Architectures

The goal of this research is to develop a methodology that can be used to compare the performance of various parallel architectures for given application programs. This methodology consists of an architecture-independent intermediate program representation for the application under study, and performance models for each architecture of interest, based on that intermediate representation. The comparison procedure is then to translate the application program into the intermediate representation, and to evaluate each performance model using that information.

The development of the intermediate program representation is at a preliminary stage. We are investigating a graph structure of the vector and scalar operations of the program (represented as nodes) and the control and data dependencies (represented as arcs). This type of notation can represent any kind of parallelism, and does not tend to favor one particular type of parallel machine over another.

The performance models for each parallel architecture combine

the information about the nature of the programs (type and number of functional operations and type and number of data/control dependencies) with the characteristics of a particular type of machine (type and number of functional units and machine control structures).

Preliminary versions of the models for instruction-pipeline, vector, array, multi-processor, and data-flow machines have been developed.

Future work will consist of refinements of the program representation and the performance models, development of a translator to convert programs written in a high-level parallel language into the intermediate program representation, and testing the methodology with real application programs for which meaningful results can be produced.

12.2.3 Data Flow Architectures

The data flow architecture is claimed, at least on a theoretical basis, to be the most highly parallel architecture in that instructions execute as soon as their input data is available. Unfortunately, a survey of the literature has shown a rather haphazard approach towards formalizing data flow, and the question of implementation has been largely avoided. Our aim is to fully understand data flow mechanisms so that constructs which are essential to high level languages can be provably implemented at the machine language level. By formalizing what is needed to implement a data flow process, it will be possible to compare the data flow approach to some of the better understood parallel architectures in terms of space/time tradeoffs. To date we have made a fairly thorough investigation into the attempts of others, and we have rigorously defined the interaction and state transition of a computational node (the most basic element of a process). We have conceptually separated the flow of data from the flow of control, and have begun work on integrating the two into higher level primitives.

12.2.4 High Level Language Oriented Computer Architectures

The development of a systematic methodology for the design of a directly interpretable (machine level) language (DIL), given the specifications of the host hardware and a given high level language (HLL) to be executed on it, forms the basis of our research in the area of high level

language oriented computer architectures. The design of a suitable DIL for a specific HLL is equivalent to the design of an architecture directed to a single language; the optimal or near-optimal interface (between compilation and interpretation) which such a DIL should ideally represent is the medium through which the HLL would be matched to the host architecture.

As an immediate objective to achieve the above design methodology, we are in the process of formalizing the syntax/semantics of a general class of DIL's. Such formalizations have been proposed for HLL's in the past, although the semantic part of such formalizations is still in many ways an incompletely solved problem. An extension and formalization of Knuthian or Knuthian-type semantics as applied to DIL's as well as HLL's is being pursued at the present time. We intend to develop, as a next step, a set of systematic transformations to map the syntactic/semantic definition of a HLL into the corresponding definition of its well-matched DIL. An "attributed" translation grammar for use in this mapping process will be defined. It is surmised that a common semantic definitional aid to supplement the syntactical descriptions of HLL's and DIL's will help in the automatic construction of the semantic analyzer part of the compiler used in such a translation process. The HLL's which are the focus of attention at the present time belong to the class of block-structured languages such as ALGOL, PASCAL and PL/1.

12.3 Computer System Organization

12.3.1 Modelling of Multiple Processor Virtual Memory Systems

An analytic model is being developed to describe the paging performance of multi-processor virtual memory computer systems. Variables considered include the number of processors, configuration of secondary "drum" memory, number of jobs in the system, overhead time per fault, and the faulting behavior of individual jobs.

A computer simulation of such systems has been written to provide a data base which can be used to verify the accuracy of the analytic model over a wide range of system configurations and job loads. This data has also been useful for model refinement by suggesting functional

relationships and dependencies.

As the model is developed it becomes possible to simply and analytically compare various designs. For instance, one trade-off has been examined between a system with P parallel processors and an identical system with a single processor which is P times faster. This trade-off has been investigated for several types of faulting behaviors as well as various numbers of jobs and types of drum memory.

In addition to allowing design trade-off to be examined, the analytic model discloses the functional dependencies of system performance upon the system configuration and job load parameters, and thus identifies the parameters which directly affect system performance. This identification is especially useful in determining those characteristics of the faulting process which influence system performance.

12.3.2 The AMP-1 Multiple Microprocessor System

The AMP-1 system uses eight Motorola 6800 microprocessors with shared memory. It was designed and implemented to perform experiments dealing with performance evaluation of alternative system configurations within the selected class of architectures.

A hardware monitor has been developed for automatic collection of data, accessible on line, regarding run time, memory access conflicts and other monitorable events. Memory protection logic has been added to the system. A Concurrent PASCAL interpreter is now available as well. The AMP-1 is very likely the first multiple processor to support Concurrent PASCAL. Intensive evaluation of multitasked jobs has begun using the AMP-1. The results of this analysis are reported in Section 12.4.1 below. The AMP-1 is now a viable tool for performing the research for which it was intended.

12.3.3 Cost Effective Parallel Processor Design

The focus of this research is on the utilization of shared resources in a parallel processor system. Possible resources include functional units, memories, busses, or processors. Initial work has focused on the behavior of low level tasks where each task is very primitive, possibly a single instruction, and the resource utilization pattern of

the task is fairly well defined in advance of its execution. For this class of problems, analytic models (Markov models) are useful in predicting and optimizing performance among a collection of tasks sharing resources in a parallel/pipeline computer.

As one considers the execution of more complex independent tasks, the use of analytic techniques to effectively share resources becomes less practical. The number of states in an analytic model of a complex system quickly becomes astronomical precluding any analysis or optimization for many systems of interest. In some cases, approximating assumptions help simplify the analysis, however, they usually lead to inaccurate measures of system performance. If one wishes to study realistic large scale parallel computer systems, any accurate analytic description becomes intractable.

We have initiated work studying the feasibility of a design language for the description, simulation, evaluation, and optimization of advanced computer architectures. The most important features of this design language are descriptive clarity, and its use as a simulation tool for the evaluation and enhancement of candidate architectures. Of course, the design language is especially meant to support the description of complex systems of parallel processors sharing resources.

This design language is meant as a tool for the study of advanced computer architectures. As such, it is only useful if it supports the efficient description and simulation of prospective advanced architectures. We have surveyed the existing languages and concluded that language support for analysis of parallel architectures is very poor. This implies that the overhead effort in evaluating an advanced architecture is unacceptably large. While existing languages support the description of serial processors, parallel languages have largely addressed operating system issues and not the problems of parallel computer design. A parallel computer design language is both desirable in that it will yield tangible benefit, and feasible from the standpoint of implementation.

With such a tool, a library of parameterized components can be collected. Thus, independent predefined modules describing interleaved memories, processors, function units, or busses can be quickly assembled to evaluate the performance of a candidate system. This allows the

designer to evaluate far more complex systems than would otherwise be possible through any analytic approach. Modules may be re-assembled into new configurations allowing the very efficient evaluation of wide classes of parallel processors.

The current work involves the selection of a suitable syntax for a parallel computer design language. The syntax is being evaluated by coding design descriptions of advanced architectures. Thus, we can evaluate the time saved in describing an advanced architecture in a suitably selected design language over that experienced in an existing language. Further, we are evaluating the suitability of the language as a descriptive tool, that is, how well does it document the design.

12.4 Problem-Oriented Architectures

12.4.1 Multiple Instruction Stream Processing

As the developments of many physical components used in the computer have approached their theoretical limits, the most promising alternative for further improving the computer performance is probably parallel processing. However, as the advances in technology have also greatly reduced the cost of physical components so that the exploration and exploitation of parallelism is much less constrained by physical limitations, the logical constraints in conventional algorithms, such as precedence waiting, mutual-exclusion lock-out, etc., still significantly limit the enhancement of performance using parallel processing.

This research mainly concerns the actual implementations of conventional algorithms on parallel machines and analyzes the performance-degrading overheads. The effects of performance as a function of the available physical resources in the system, the dimension of the problem, and different schedulings of various tasks are also to be investigated.

Based on a bottom-up approach, two kernels, matrix multiplication and solving systems of linear equations, particularly important for the finite-element method of structural analysis and other matrix oriented applications, have been analyzed and implemented on the MIMD machine, AMP-1, developed at CSL.

A speed-up of 6.74 using seven processors in multiplying two

32 X 32 matrices can be achieved and the major degradation from the ideal speedup of 7 comes from memory contention. The performance, therefore, benefits significantly from increasing the number of memory modules and the address interleaving. A hybrid model which uses a multiple-instruction-stream multiple-shared-resource pipelined processor model modified by the logical structure of matrix multiplication has been derived. The speed-ups using up to seven processors predicted by this model match the measured data from AMP-1 thus far collected within 0.5 percent. A survey report on various implementations of matrix multiplication on many different machine architectures has been prepared.

Solving systems of linear equations, on the other hand, has much more complex structure than matrix multiplication. A conventional Gaussian elimination algorithm consisting of normalization, reduction, and back substitution phases introduces significant synchronization overhead which, in addition to the memory contention, degrades the performance of multiple processor systems. The elimination of the overhead-causing normalization tasks and the addition of proper modifications to reduction and back substitution phases convert the conventional Gaussian elimination algorithm into an LU decomposition algorithm, which brings the speed-up using seven processors in AMP-1 up from 4.54 to 5.83. It has been shown that Cholesky's method can be similarly modified for parallel execution. An analytic model is being developed to accurately model various sources of degradation due to the logical structures of these algorithms and the availability of physical resources.

12.4.2 Fast Fourier Transforms for Synthetic Aperture Radar Processing

A study has been initiated to find efficient computer structures for 2D Fast Fourier Transform Computation. A prior conversion from the spherical coordinate system of the radar images to the rectangular coordinate system of the FFT is normally performed before the FFT is taken. The interpolation involved in this transformation is time consuming and inaccurate. We will compare this method with performing a transform directly in spherical coordinates.

In addition to the 1DFFT itself we will also evaluate efficient methods for performing the matrix transpose required between the two 1D

transforms which make up the 2D transform. The transpose problem becomes severe when a large matrix must be paged-in in blocks from disc.

12.5 Modelling and Evaluation of Large Computer Systems

12.5.1 Simulation of Multiple Instruction Stream Machines

We are in the process of evaluating a cost-effective concurrent processor organization known as a multiple-instruction stream machine or as a shared internal resource multiprocessor. This organization has many potential advantages over better known competitors such as the multiprocessor and the overlapped, lookahead processor. However, few quantitative analyses have been performed upon this organization. We have almost completed the development of a simulator for such a machine. The simulator has been constructed using the simulation language SIMULA. We intend to use the simulator to study the performance gains as a function of the number of instruction streams, degree of interleaving, extent of buffering and various priority schemes.

This project also serves another purpose. We plan, eventually, to develop a facility for research in computer architecture, a component of which would be a language designed for the express purpose of describing and simulating prospective architectures. The simulator under construction by using SIMULA, is making use of one of the most powerful simulation languages currently available. In the course of this project we have built up valuable experience with this language. SIMULA has many attractive and elegant features but also has certain shortcomings from the point of view of computer system simulation. This insight will aid us in the subsequent development of the computer design and simulation language.

12.5.2 Local Balance Networks

We are continuing our study of queueing networks for which the stationary probability distribution can be obtained analytically. This class of networks has been termed "local-balance networks" in the literature. Our previous efforts in this area had revealed the fundamental mechanism that leads to the existence of local-balance, viz., the cellular decomposability of the Markov chain that describes the queueing system.

We have now developed necessary and sufficient conditions under which cellular decomposability holds, in which case the stationary probability distribution can be obtained with relative ease. The class of queueing systems that falls into this category includes all know local-balance networks and, in addition, many others. The set of queueing networks for which an analytical solution exists has, thus, been greatly enlarged.

12.5.3 Performance Measurement and Evaluation of Large Scale Computer Systems Using System Accounting Files

The performance measurement and evaluation of large scale computer systems do not require hardware and software monitors as data collectors, but rather a comprehensive approach is described which uses only the computer system's accounting file as the data source. This data is processed into a Performance Data Base which is the primary tool of this approach, and it is used to establish meaningful and measurable performance objectives. The objectives for service are related to resource consumption by a "charging" scheme that charges a "higher" price for "better" service, and thus capacity measures (for equipment acquisition or release) relate directly to qualitative and quantitative measures of user satisfaction versus supplier's costs.

The implementation of the Performance Data Base is described and the development of specific objectives for several systems (batch, interactive) is described. Examples of the capacity measures are shown, and several examples of the simplicity, cost-effectiveness and utility of the approach are described [7].

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13.1 Introduction

The research program of the Display, Memory, and Computer Terminal Architecture Group is concerned broadly with computer-based information and communication systems in which users interact through a variety of tactile and audio input devices. Its goals are to devise human interface, terminal architecture, and system structure specifications for improving the efficiency of these information and communication systems. The report which follows describes our work concerning interactive facsimile communication systems.

13.2 Interactive Facsimile*

The objective of this research is to develop an understanding of the problems of remote technical or professional communication involving the interactive use of alphanumeric test, graphic images, pointing, and voice. In particular this work attempts to clarify the basic concepts of technical teleconferencing to provide a basis for the design of a new communication terminal which can support real time professional communication over a single digital voice channel. Such a terminal could support teleconferencing activities from any location serviced by a single telephone line to any other location in the world.

We conducted a survey [1,2] of the participants in an actual teleconference to assess the importance of various teleconferencing system characteristics. The responses to this questionnaire, while not

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under Contracts DAAG-29-78-C-0016 and N00014-79-C-0424.

conclusive, indicate effective technical teleconferences can be conducted with a two-way voice channel, an image handling system, and a remote pointer. Surprisingly, the responses also indicate that a television image of the speaker is not required. A majority of the participants would attend similar teleconferences.

13.2.1 Pointing

An important characteristic of face to face communication is the ability to point at an image that all the participants can see. In a teleconferencing system, a cursor can be used to point at objects in remote display images. The configuration of this cursor can affect its usefulness. For example, an opaque circular cursor will mask the image behind it.

A simple circular or diamond shaped cursor figure works well for the pointing applications we have examined. The circular pointer is composed of 4 concentric circles with an outside diameter of about 2 cm which is approximately 1/120 of the plasma panel display area. To permit this cursor to be visible in a variety of background images, two of the circles are composed of bright picture elements (pels) and the other two are generated by dark pels.

Our experiments suggest that the pointer location resolution may need to be equal to the display image resolution. However, high pointer resolution does not necessarily imply a high bandwidth communication line. Our experiments indicate that the remote display processor can locally generate the cursor at each sampled pointer location coordinate and can smoothly move the cursor from one location to the next. Simulations show that a location sampling rate of 10 per second which represents about 200 bits per second is sufficient for the tasks we examined.

13.2.2 Data Multiplexing

One of the major disadvantages of many of the commercially available conference systems is the need for a high bandwidth communication channel or separate channels for voice and data transmission. Our work in this area is directed toward methods of combining the voice, image, and pointer data on a single digital voice channel. For our experiments, we have assumed the voice data is digitized at 8000 samples per second using the mu-225 companding algorithm [3]. Our results are applicable to both

the Bell System T1 and the CCITT 64KB/s standard digital voice channel.

Actual technical slide presentations were tape recorded and digitized for our data multiplexing experiments. These experiments show that when the image data is transmitted during natural voice pauses, which account for at least 15% of the total time, there is sufficient time to transmit more than one 32 kilo-byte image file per minute.

A new data multiplexing technique was discovered to transmit the pointer updates. The zero crossing technique [1] inserts a single data bit in the least significant bit of the sample near the zero crossing of the digital voice waveform. This crossing is signalled by a sequence of + + - or - - + digital samples. Since the mu-225 digitizing algorithm has the highest resolution near zero, the distortion resulting from this bit substitution is negligible. Our experiments show that an average of more than 800 zero crossings per second are present in the taped presentations.

13.2.3 Minicomputer Terminal Simulator

The goal of the terminal simulator research unit is to construct a minicomputer based graphics terminal to support our remote conferencing experiments. This PDP-11/05 intelligent terminal [4] independently drives two plasma panels to simulate a graphic communication channel. Mounted on one of the displays is a 256 X 256 touch sensitive digitizer [5]. In addition, a 12 bit analog to digital converter and 16 bit digital to analog converter are available to test voice data and non-verbal data multiplexing techniques.

We will continue to use this experimental configuration to simulate interactive facsimile communication. Minicomputer programs have been written which demonstrate the operation of the remote cursors by using the touch surface to control cursors in images on both displays. Other programs simulate the mixing of voice and non-verbal data so that the resulting audio signal can be heard. Using this terminal simulator we will test the validity of new assumptions concerning teleconferencing characteristics and gauge the difficulty of realizing these system features in an actual network.

13.3 Optical Disk Memory System*

The objective of this research is to devise techniques for realizing a low cost 10^{10} bit local mass store for use with processor-based terminals. To do this we have been using the optical video disk technology that is presently receiving great attention for use in home entertainment systems [1]. These systems store 10^{10} bits on a 30 cm diameter disk of thin plastic. The emphasis of our research is to find a system configuration that will allow worst case access time for any information on the disk to be less than 100 milliseconds and still maintain low cost.

A major challenge with this system is the design of the servo system that controls the deflection mirror. In our system the mirror must deflect a laser beam to any of 5000 tracks. This means that the demands of the servo system are more than 100 times greater than those of typical video disk systems. The progress in the past year has been in developing control strategies and circuits that now allow the servo system to reliably and accurately keep the laser beam centered on a track in the presence of various noise sources such as excentricity of the rotating disk, mechanical vibrations, laser noise and noise from dust and irregularities on the disk.

13.4 Device Characterization of the AC Plasma Display Panel*

The AC plasma display panel has received widespread acceptance as a viable product throughout the display community. A great deal has been learned through the years about the electrical behavior and the physics of the discharge process. It is however difficult to quantitatively characterize the operation of the device and thus many of the details of operation have gone unexplored. As discussed in last year's progress report we have built a computer controlled curve tracer that makes the electrical characterization much less tedious. With this instrument many details are now being explored which when understood will allow the device to be manufactured for lower cost.

The principle characteristic curve for this device has long been recognized and it is called the voltage transfer curve [7,8]. From this

*This work was supported by the University of Illinois Computer Based Education Research Laboratory.

curve an engineer can determine various parameters such as the memory margin and the address voltages necessary for perfect one shot addressing. Our curve tracer presents this curve in real time to the experimenter [9, 10].

Recently we have discovered that for a single plasma cell there are two of these curves that are needed to describe its operation. These measured curves are shown in Fig. 13.1. One curve must be used when the cell is initially in the off state and is transiting to the on state. The second curve is used in the on to off transition. The fact that our measurements indicate that two curves are needed is highly significant since all previous theory explained the characteristics in terms of one curve.

The impact of this result can be illustrated by discussing the effect of two curves on the memory margin which is defined in terms of the range of applied voltages over which the plasma cell will maintain its memory characteristics. The theory worked out long ago assumed a single curve and showed that the memory margin could be determined from the shape of that curve. When two curves are included in this theory the memory margin is dependent both on the shape of the curves and the separation between the two curves. For the curves shown in Fig. 13.1 the separation of the curves accounts for 60% of the total memory margin. Thus we have discovered a significant new memory mechanism that in this case dominates the previously understood single curve mechanisms.

The exact physical reasons for the two curves are still under investigation and complete understanding will probably not occur until we have increased the capabilities of the curve tracer. The system diagrammed in last year's progress report allowed a minicomputer to vary the peak voltage of the sustain waveform applied to the plasma panel. This meant that a very restricted set of voltage waveforms could be applied to the panel. We have built and are presently debugging a system that will allow direct software control of the sustain and address waveforms. This will be a very significant advance to the curve tracer since the electrical characteristics are highly dependent on the shape of these waveforms and the ability to quickly modify these waveforms will allow the careful exploration of many new operational characteristics. Computer control of the

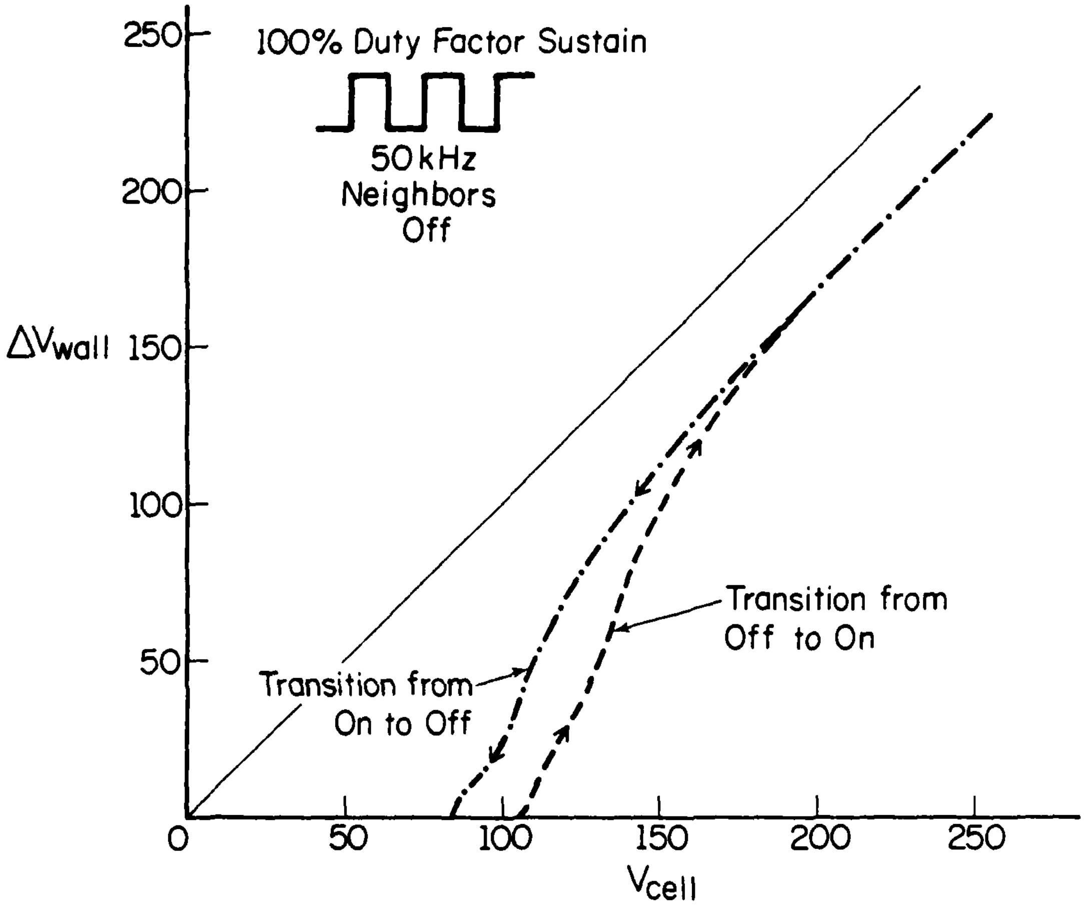

Fig. 13.1 Voltage transfer curves measured for a single plasma display cell showing the need for two curves to describe cell behavior.

waveform shape will also allow the use of new strategies for measuring the voltage transfer curve which will probably greatly help the understanding of why two curves are necessary.

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14.1 Introduction

During the past year we have continued our investigations in the area of the design and analysis of computations. We have pursued our well-established research in computational geometry, where a variety of planar problems have been solved, and in parallel computation, where new promising avenues of considerable practical significance have been opened. In addition, new interesting studies have been undertaken. In the area of combinatorial problems, we have studied two-dimensional bin packing, data base organization, matching, and generation of permutations. The important relationship between computation time and available storage has been analyzed for a number of problems. Each of these areas will now be individually reviewed.

14.2 Computational Geometry*

In the field of computational geometry we investigated various applications of a data structure called a segment tree, which we have already used for an efficient solution of the point-location problem [1] The first application we have considered is the efficient determination of the contour of a union of iso-oriented rectangles [2]. This problem has applications in the design of VLSI circuits, structuring geographical data, computer graphics and two-dimensional data organization in bubble memories.

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We have obtained an algorithm which finds a p-edge contour of a union of m rectangles with sides parallel to the coordinate axes in time $O(m \log m + p \log (2m^2/p))$. This is $O(m^2)$ (optimal) in the general case and $O(m \log m)$(optimal) when the union of rectangles does not contain holes.

Another geometrical problem, investigated in [3], is that of finding a Manhattan path through a collection of vertical and horizontal segments on the plane. A Manhattan path is an alternating sequence of vertical and horizontal segments, where adjacent segments overlap. In [3] we have described an algorithm which finds a shortest (in the sense of the number of segments) Manhattan path in a collection of n segments in time $O(n \log^2 n)$. One of the related problems considered is cutting of a figure on the plane in the form of a hole-free union of possibly overlapping rectangles into the minimal possible number of disjoint rectangles. An algorithm, using the technique of Manhattan paths, to solve this problem in $O(n^{3/2} \log^2 n)$ time, where n is the number of edges of the figure, has been presented in [3].

We have also considered the problem of finding the intersection of planar maps, which is relevant to several applications in geography, management, and design automation. The proposed techniques are significant adaptations of an elegant method [4] for finding the s intersections in a set of line n segments arbitrarily placed in the plane. It had been shown [5] that the intersection can be reported in time $O((n + s) \log n)$; we have now shown that within the same time bound not only the intersections can be reported, but also the boundaries of the resulting planar subdivision can be described [6]. Finally, when the regions of the two maps are all convex, the algorithm can be sped up to run in time $O(n \log n + s)$, i.e. optimally in s [6].

14.3 Parallel Computation*

The great technological progress embodied by VLSI has made it

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possible to conceive large systems of processing elements cooperating in the execution of parallel algorithms. Unfortunately, here the situation is very different from that of serial computation, where the RAM machine represents a universally accepted model. With respect to this basic difficulty, there are two important viewpoints. The first ignores the problem of specifying a technologically feasible connection of processing elements (PE), and considers algorithms for a system where any pair of PE's is connected (data-flow machine); the second viewpoint approaches the same class of problems with respect to highly constrained interconnecting architectures.

The first approach is certainly not without merit, because it aims at uncovering the inherent data-dependence of given problems. From this viewpoint, we have studied the design of parallel algorithms for selected geometric problems [7] . Specifically, we have initially developed an algorithm for the determination of the convex hull of a set of points in the plane with $O(\log N \log\log N)$ parallel steps on at most 2N processors (with a speed-up of $O(N/\log\log N)$. Next, we have developed a point-location algorithm, that is, an algorithm for finding the region of the N-region planar subdivision which contains a given test point P. Adapting a previously developed technique [1] , while the actual point-location runs in time $O(\log^2 N)$ on one processor, the supporting data structure can be constructed in $O(\log^2 N \log\log N)$ parallel steps on $O(N)$ processors. The two described techniques can be used to solve another interesting and significant problem: the determination of the convex hull of a finite set of points in 3-space; we have shown that this problem can be solved in time $O(\log^3 N \log\log N)$ on $O(N)$ processors. Finally, by exploiting the idea of dual-transformations of geometric objects, and the just mentioned 3-dimensional convex hull algorithm, we have developed parallel algorithms for the construction of the Voronoi diagram in the plane. (As is well-known, the Voronoi diagram for a finite set S of points in the plane is a subdivision of the plane into regions so that each region is the locus of the points which are closer to a member of S than to any other member.) The constructed algorithm uses $O(\log^3 N \log\log N)$ steps on $O(N)$ processors.

As regards parallel computation with constrained architectures, several workers have suggested that processor interconnection should be

limited to planar links between topologically neighboring cells (arrays or meshes). Although such extreme designs are certainly well suited for current VLSI technology, they are not suited for efficiently implementing various fundamental problems, such as sorting and convolution. Indeed, good algorithms for solving these problems intrinsically require data movement between processors which are topologically far apart. Therefore, we have proposed [8] a new interconnection of processors, called the cube-connected cycles, which is remarkably suited for implementing efficient algorithms such as Fast Fourier Transform (FFT), Sorting, etc. This architecture consists of "cycles" of processing elements; in turn, these cycles are interconnected according to a binary k-cube. By combining parallelism and pipelining we were able to achieve the following results:

(1) The number of connections per processor is reduced to 3; Processing time is not significantly increased with respect to that achievable on the binary cube structure;

(2) Programs for the individual modules are obtained in a systematic way from a standard recursive description of the global algorithm;

(3) The overall structure complies with the basic requirements of VLSI implementation: modularity, ease of layout, simplicity of communication among the processing elements, simplicity in timing and control of the entire system;

(4) Finally we are able, without inventing any drastic departure from classical algol-like languages, to provide fully accurate descriptions of our parallel programs.

The proposed interconnection remarkably lends itself to VLSI realization within a recently proposed model [9]; in this model, it can also be shown that the CCC is optimal for a number of fundamental algorithms, such as FFT and merging.

14.4 Combinatorial Problems*

Many problems, such as allocating shared storage to parallel

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processes, cutting stock problems, etc., are modeled by two-dimensional bin packing. In the model, a finite list of rectangles is packed into a rectangular bin of finite width but infinite height, so as to minimize the maximum height used. The packed rectangles cannot overlap, nor can they be rotated. Since the problem of finding an optimal packing is NP-complete, approximation algorithms have been studied. As a measure of an algorithm's optimality, we examine the ratio

$$\frac{A(L)}{OPT(L)}$$

where A(L) and OPT(L) denote, respectively, the height of the packing of a list L of rectangles produced by the algorithm A, and the height of an optimal packing.

Most of our work has involved obtaining lower bounds on (A(L)/OPT(L)) for various classes of algorithms. We have shown [10] that, for any algorithm which packs the rectangles in the order received with no lookahead or moving of rectangles already placed, there is a list L for which $(A(L)/OPT(L)) \geq 2 - \delta$ (for any $\delta > 0$). Specific bounds of this type have been obtained for algorithms which allow some simple preprocessing of the list before packing, such as decreasing width, decreasing height, increasing width, and increasing height [10,11]. It has also been shown [12] that for the well-known "bottom-left" approach, <u>any</u> preprocessing has a worst case lower bound of at least 5/4. Finally, an asymptotic lower bound of $\alpha = 1.536$ has been obtained [13] for the one-dimensional bin packing problem, which extends to two dimensional packings and gives asymptotic 1.536 lower bounds for packing rectangles in order of increasing or decreasing height or increasing width.

Interesting combinatorial problems arise in the design of files. Our objective has been the organization of files in order to achieve the simultaneous minimization of access time and storage space. The problem in its simplest version calls for testing whether a (0,1)-matrix has the consecutive ones property, i.e. whether its rows can be permuted so that the 1's appear consecutively in each column. We have described four natural possibilities of generalizing this property, in an attempt to

make it more adequate for practical applications. We have shown that all four approaches lead to NP-complete problems [14], which indicates the limitations of the approach based on the consecutive one's property.

Matching problems constitute a traditionally important topic in combinatorics and operation research. We have investigated [15] matching problems in bipartite graphs of a special type, called convex. For graphs of this type we have found an algorithm which constructs a maximum matching in $O(m + nA(n))$ time, where $A(n)$ is an extremely slowly growing function related to the functional inverse of Ackermann's function. We have also shown how to produce from such a matching in $O(m + n)$ time, a maximum independent (mutually nonadjacent) set of vertices.

There has been a considerable interest in efficient methods of generating all permutations of n objects on a computer, due to their relevance to discrete optimization techniques. We have found a general principle which enabled us tc obtain a whole class of permutation generation methods [16]. Our principle makes it possible to design a permutation generation method with certain special properties which are very desirable when the algorithm is used as a part of a backtrack program.

14.5 Space-Time Trade-Offs*

Storage space and computation time are two important parameters that reflect, at least in part, the real cost of computing. In selecting an algorithm for a problem, it could be very useful to have knowledge of lower limits on values of space and time that can be achieved simultaneously.

During the year progress has been made in our attempts to understand the dynamics of the tradeoff between computation time and temporary storage space in the design of algorithms. The results obtained for three different problems are described below.

Many high-level languages permit the use of recursion and hence allow linear recursion in which each execution of a procedure activates at most one invocation of itself. Linear recursion is usually implemented

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with a stack when a compiler either cannot or does not replace it with iteration. The size of such a stack will grow linearly with the depth of recursion and may in fact occupy much more storage space than the procedure itself. In [17] we have developed a general method based on a simple graph model to reduce the storage space required to implement linear recursion at the expense of computation time. If n is the depth of recursion, $p = n^{1/k}$ is the stack size, then the computation time $T_p(n)$ remains linear in n, which implies that a large decrease in space can be achieved at the expense of a small increase in running time. We also exhibit the class of algorithms which achieve these optimal space-time exchanges and show that at least one of these algorithms is easily implemented.

We assume that straight-line algorithms are to be employed for multiplication of n-bit integers and we assume that these algorithms are to be executed on machines which have a limited number of storage locations (or space S) [18]. The space and time required for binary integer multiplication is lower bounded by $O(n^2)$, while upper bound of $O((n \log n)^2)$ on $(S + 1)T$ follows from a simple modification of the standard multiplication algorithm.

Finally, we have considered the problem of computing strings of elements from a semigroup. We have shown that if the space $S \geq 2 \log_2 n$, then $S \cdot T \leq O(n(\log_2 n)^2)$, while, for $S < 2 \log_2 n$, $S \cdot T$ increases with decreasing space until $S \cdot T = O(n^2)$; it should be noted that the naive algorithm for this problem achieves the bound.

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15.1 Manipulation and Assembly*

Research continued in the area of robotics. Algorithms were investigated for utilizing visual feedback and force feedback for positioning [1]. The Robot Servo System language (RSS) was developed to specify the activities for the robot servos. Using this system a programmer may specify powerful sensor driven robot tasks in a manner which corresponds closely to his intuitive ideas about how the task should be performed.

The software implemented allows the manipulator to be programmed in terms of constraints. A manipulator position is described by specifying a reference point, attached to the arm, and a goal position or constraint for that point. Similarly, an orientation is described by reference lines attached to the arm and constraints for those lines. Force and torque are described by a reference point and the desired force and torque vectors at that point. A split-screen stereo adapter for the TV camera provides two views of the scene and allows depth information

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to be extracted. Visual servoing is achieved by specifying both the reference and goal positions or orientations in terms of data from the vision processor, and by tracking features of the arm or of the object being moved by the arm.

The system was tested, demonstrating its ability to perform a variety of tasks using visual and force feedback. Included among these tasks were the insertion of a circuit board into a specified holder, the insertion of a bolt into a hole and the turning of a crank. Currently, work is being done to implement a second robot arm to extend the overall capabilities of the system.

15.2 Visual Information Processing and Recognition

Research was performed in the area of computer vision. Algorithms were developed for low-level feature extraction, for high-level modeling and for feature matching.

15.2.1 Bottom-Up Recognition*

A facility for aiding low-level vision research has been completed. Methods were investigated for performing bottom-up artifact modeling and recognition [2,3]. This system is implemented on a DEC KI-10 in BLISS-10, MACRO-10, and FORTRAN. Sequences of stereoscopic pairs of images are digitized, frame by frame condensed to vertex-string-surface graphs (V-S-S graphs), and re-encoded as half chunk graphs (H-C graphs). The single frame processing requires approximately 20 minutes per image. Single image derived H-C graphs are matched by stereo pairs for depth, and by time interval pairs for motion. By using depth cues, motion cues and intensity feature labels, individual object subgraphs are segmented. Individual object graphs are matched with and/or entered into an object graph library.

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We experimented with two new edge detection algorithms, an edge-based region aggregation algorithm, a scan line oriented vertex-string encoding algorithm, a half chunk graph matching algorithm, and a histogram-based graph matching algorithm. We also worked with the idea of the "half chunk", an elemental curvature element which can be used to form scale and coordinate system invariant object graphs (or "feature" centered object models).

15.2.2 Feature Network Matching*

Investigations have continued in the area of feature network matching. During the past year several programs have been examined which analyze digitized color images and convert the images into networks of features [4,5]. These programs are based on region growing and edge detection algorithms. The programs have also been transcribed into the language C so that they can be used interactively on a PDP-11 Unix system with a RAMTEK color graphics display. The networks consist of surface, edge, and vertex nodes which are connected by links based on the adjacency of the two features. The nodes also contain color, texture, and multidimensional shape information. Considerable forethought has been given to using a homogeneous format for representing the surface, edge, and vertex nodes. This in turn has resulted in simpler and more uniform software for processing these nodes. The networks are initially planar, however, as multiple images are processed in a camera motion sequence the network takes on a three dimensional character. Ultimately, the three dimensional network becomes a computer model of the objects in the scene. A preliminary analysis of algorithms for matching these types of networks has been completed, and an operational analysis of these algorithms is now in progress.

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15.2.3 Parallel Methods for Picture Processing*

During the past year this research has been concerned with low-level parallel techniques of picture processing. Of late, our interest has centered around how to represent the picture hierachically based on such cues as gray level, color, edges, corners, axes of symmetry, texture, and so on. This representation is in the form of a tree structure where the top level node represents the entire scene and lower level nodes represent finer divisions of the picture. Of course, this representation is recursive in the sense that the top level node could easily be a lower level node in some other picture.

The representation is developed using the following mechanism: The picture data from the camera are embedded in hexagonally tessellated cellular automata. Each cell then forms a structure describing in various ways what sort of information it contains. At this point each of these structures (called a "message") is "broadcast" outward from the cell which produced it. Each message can interact in several ways with other messages and with the contents of cells through which it passes. For instance, two messages coming from opposite directions and describing two cells which have opposite but equal local gradients provide evidence that the cell in which they meet lies on an axis of symmetry. See [46] for more details.

15.3 Computer Aided Decision Making

Research was continued in the area of computer aided decision making. The design of an intelligent onboard software system was continued. A hierarchical structure for representing knowledge about aircraft systems is being investigated which will aid planning, decision making, consequence analysis and trend analysis in real time environments such as aircraft in flight. In addition, the design has continued on a system for locating faulty components in analog circuit boards.

*This work was supported by the Office of Naval Research under Contract No. N00014-75-C-0612.

15.3.1 Safety Enhancement by Computer Reasoning (The SECURE System)*

Work has continued on the conceptual development of a system which uses artificial intelligence methodology to monitor aircraft systems, to detect faults, diagnose the faults, and to suggest recovery procedures from these faults. The SECURE system is being designed so that it does not increase the pilot workload, but rather serves as an additional, untiring crew member.

A flight monitor using stored references has been implemented. It is used to verify our ideas about the sequence of contexts in flight and to provide the monitor module for the other modules in the intelligent onboard computer system to interact with. It is being designed with knowledge to handle unexpected situations as they occur. The knowledge required spans all levels of flying including knowledge of the general goals of a phase of flight, the aircraft aerodynamic performance capability, the flight maneuver techniques, and the aircraft subsystems.

The knowledge base is divided into four levels. Level one specifies the flight phase goals and describes the overall characteristics of a flight, level two contains aerodynamic knowledge and deals with the aircraft trajectory and the forces that influence it, level three consists of the aircraft maneuver knowledge and holds the knowledge about the flight controls used to directly affect the aircraft trajectory as a set of relationships between the aerodynamic quantities of level two and the physical aircraft control settings, and level four has the knowledge about the aircraft subsystems that enable the aircraft to fly.

Investigations have continued on a software diagnosis subsystem which isolates faults to aircraft subsystems of instruments. Extending the capabilities of the original Instrument Verification system, this

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system uses subsystem performance models, along with knowledge of secondary effects of failures to diagnose faults. A system of failure patterns initially reduces the search space by triggering specific search routines when failures are detected. A model of subsystem functional dependencies is then traced to narrow the search further. When ambiguous situations occur, and it is not certain which subsystem or set of subsystems is failing, the diagnosis system may suggest to the pilot an experiment which will clear up the ambiguity. For instance, if one of the engine parameters indicates a possible flame-out, and the other engine indicators appear normal, a diagnostic experiment to reduce the engine throttle setting by 50% will give a clear picture of the ambiguous situation.

15.3.2 Automatic Analog Test Program Generation*

Work on a system for automatic analog test program generation was continued [6,7]. The system accepts as input a topological description of an analog circuit board and produces a test program for the automatic test equipment (ATE) to isolate the component causing board failure. The system develops an understanding of the circuit by applying the local expert knowledge in a system of function procedural models. The system then generates the set of tests based on that understanding.

The first task of the system is recognition of functional entities called subcircuits. The algorithms for topological recognition are based on the propagation of subcircuit boundaries. Each recognized subcircuit defines new recognition start points, called anchor nodes. The initial set of anchor nodes consists of GND, V-sources, circuit nodes, and the terminals of active elements such as op-amps. An approach to functional recognition of entities by using directed simulation is under investigation.

Given the functional partition, the next task of the system is to isolate the subcircuit causing board failure. We have developed a

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*This work was supported in part by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contracts DAAG-29-78-C-0016 and N00014-79-C-0424.

channelization algorithm to identify minimal, independently testable sets of subcircuits. A set of procedural models, each an expert in the functional testing of a particular subcircuit type, is being coded. Each subcircuit function imposes a demand on the synthesis of the test signal to introduce at the channel input. Methods are being investigated to propagate these functional demands from the target subcircuit through preceding channel subcircuits to the channel input.

Given the faulty subcircuit, the last task is to identify the component causing that subcircuit to fail. Methods to accomplish this are being investigated and include extending the procedural models to contain an understanding of the symptoms of component failure on a function. Other approaches include applying circuit theoretic analyses locally.

15.4 Natural Language Access to a Large Data Base*

Work has continued on natural language data base front ends. JETS [8] is our natural language question answering system, designed to interface users to a large relational data base. JETS is the successor to the PLANES system [9], and operates in the same domain: a large data base of aircraft flight and maintenance data. The architecture of JETS is designed to extend its conceptual coverage to better meet the coversational and data base usage requirements of users. The implementation of JETS is designed to gain a high degree of closure over concept manipulation, contributing to the problems of perspicuity and scale.

15.4.1 Evaluation of Natural Language Systems

Work on the evaluation of natural language processors has continued, with current progress being defined in [10]. The performance of PLANES and another question answerer, The Automatic Advisor, was

*This work was supported by the Office of Naval Research under Contract No. N00014-75-C-0612.

studied in the context of actual user dialogs. A distinction between two characteristics of natural language processors was found to be very useful. These characteristics are the LINGUISITIC and CONCEPTUAL COVERAGE of the programs. Much of the attention in natural language research has been focused on linguistic coverage, and language processors were found to have faults in these areas. However, the most interesting faults were found in the conceptual coverage of the systems. Conceptual coverage is just beginning to become recognized as an important problem in natural language research.

Along with the two types of coverage in natural language processors, two terms were defined to represent a measure of the adequacy of linguistic and conceptual coverage, with respect to the needs of the users. The measures are called linguistic and conceptual completeness.

15.4.2 JETS

JETS is a response to the insights gained through the evaluation of PLANES. Its preliminary architecture is described in [8]. Problems with linguistic coverage in PLANES were primarily syntactic. JETS will contain a powerful syntactic parser. Problems with the conceptual coverage of PLANES are common in nearly all contemporary natural language processors: (1) ellipsis requires more complete coverage, (2) coreference requires more complete coverage, (3) a greater range of speech acts is required, (4) some form of closure over semantic interpretation is required. In addition, a thorough evaluation will be conducted on the resulting program.

Much of the past year has been spent in studying the problems involved and in developing a design. The literature on natural language processors was surveyed with particular attention to formalisms for handling problems of semantics and dialog. A promising technique for gaining closure over semantic interpretation was designed. The problems of ellipsis and substitution have been decomposed into three subproblems: substructure ellipsis and substitution, superstructure ellipsis, and pragmatic ellipsis. None of the previous work on expanding the accepted range of speech acts appear adequate for JETS. This part of the design is still in process. An implementation of JETS has been begun.

15.4.3 The Semantic Intergretation of Noun-Noun Modification

During the last year we have continued to study the semantics of certain types of basic noun modification, with a focus on the difficult problem of noun-noun modification. We believe that this area provides a good vehicle for advancing our understanding of the semantics of natural language because: (1) Noun-noun is a highly productive form in English, (2) it has received little attention to date, and (3) the results can be of immediate and practical use.

The goal of this research is the design of a system which will interpret the meaning of instances of simple noun modification. This system will be a component of JETS.

This research on noun modification addresses both components of coverage, conceptual and linguistic (see above). Extending the linguistic coverage is the direct goal of this work. The semantic representation that JETS builds should not be sensitive to the stylistic variations in the way a concept is described. For example, we want to build similar representations for the following phrases:

engine housing acid damage
acid damage to engine housing
acid damage to the housings of engines
damage by acid to engine housings
damage resulting from corrosion of engine housings by acid
corrosion on engine housings
engine housing acid corrosion damage

This requires that the semantic interpretation rules be able to discover or infer the concepts to which the words in the phrase refer and the underlying relationships between them. See [11] for more detail.

15.4.4 Problem-Solving Frames

The description of JETS so far has centered around ways of expanding the coverage of the system. However, nothing has been done to help the system develop a plan to extract the required information from the database in the form the user intended. Problem-solving frames are introduced to describe problem domains and search strategies. They can

range from very general sketches of a particular series of problem environments to specific suggestions on how to answer a certain request. The latter problem-solving frame could even be encoded in English—where a sequence of English instructions can specify what needs to be done to answer the main request; existing programs (e.g., PLANES [9]) can intepret the English instructions as a program. Problem-solving frames will have to work jointly with the frames used during the parsing and semantic analysis stages (see above). Those frames describe the objects and events of the JETS' environment and how they are related to the data in the database. Information gathered by those frames can be used to extract appropriate values to fill the empty slots in the problem-solving frames in order that the whole frame may become instantiated. Our overall goal is to turn the user's request into a "well-defined problem," i.e., one which has complete information stated in a form that the solver can understand, and which can be executed by a systematic algorithm. Missing information will be filled in through general world knowledge or from the current dialog context.

15.5 Browsing in Large Databases*

The formation of databases containing information on mechanical systems for troubleshooting purposes has become increasingly popular and important. Examination of these databases by humans can be very costly. A system called BROWSER [12] has been developed to heuristically search a database containing information on Navy aircraft with little or no human intervention. BROWSER searches the database guided by models and heuristics looking for intersting patterns or configurations. The user is then notified of the existence of these patterns.

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15.6 PLANSYS - A Flexible Planning System*

In the last two decades, we have learned a great deal about making a computer automatically determine a plan of action in response to a request from a user. Research results show that we have effective methods to deal with these kinds of "problem solving requests" in a number of experimental problem domains. However, attempts to extend these methods to other problem domains have not been very successful. Existing problem solvers are not "open minded" enough to accept any but their own problem solving methods; results from other programs cannot easily be merged.

PLANSYS is a very "open minded" problem solver [13]. It can comfortably host a large number of problem solving techniques, and can even mediate conflicts between various techniques. Because of its "open mindedness," PLANSYS's ability is close to the sum total of existing problem solving programs. PLANSYS also forms a practical formalism for representing procedural knowledge in general.

15.7 Visual Analog Representations for Natural Language Understanding*

In order for a natural language understanding system to truly "know what it is talking about," it must have a connection to the real world correlates of language. For language describing physical objects and their relations in a scene, a visual analog representation of the scene can provide a useful target structure to be shared by a language understanding system and a computer vision system.

We have implemented a program [14,15] which generates visual analog representations of English sentences which describe a scene. A sequence of sentences can result in a fairly elaborate model. The program

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can answer questions about the relationships of the objects in the scene, even though the relationships in question may never have been stated explicitly in the original scene description. Results suggest that the direct testing of visual analog descriptions may be an important way to bypass long chains of reasoning, and to thus avoid the combinational problems inherent in such reasoning methods. Other work relating language and perception is described in [16,17].

15.8 Human Decision Making and Human-Computer Interaction

15.8.1 Pilot Interaction With Airborne Automated Decision Making Systems*

Automation is increasingly finding its way into the aircraft cockpit. To a certain extent, the aircraft will soon be able to almost fly itself. This trend leads one to question the role of the pilot in semi-automated and automated aircraft.

A primary thrust of this research has been formulation and solution of the problem of allocating decision making functions between pilot and computer. One approach is to use the computer as a backup decision maker, assigning tasks to it as the load on the human becomes excessive and taking away responsibility as the load becomes manageable for the human. This approach is attractive in that it allows the human to maintain an overall perspective for the system without having to actually perform all of the tasks.

This approach has been investigated from a theoretical point of view using a queueing theory formulation [18]. A procedure for optimally determining when the computer should be utilized has been developed [19]. These ideas are now being studied in two realistic settings. One of these settings involves the monitoring of multiple

*This work was supported by the National Aeronautics and Space Administration under NASA-Ames Grant NSG-2119.

dynamic processes [20,21]. The other setting involves computer-aided flight management [19,22,23,24]. The goal of these efforts is to demonstrate the usefulness of the approach while also gaining an understanding of the human's abilities to perform in such a computer-aided environment.

Several new efforts have also recently been initiated within this research area. These include investigations of airborne management information systems [25,26] as well as prospects for mathematical models of human behavior in realistically complex tasks [27]. This latter effort has recently been directed at developing methodologies for assessing the pilot's planning activities as a function of varying degrees of automation.

15.8.2 Human Decision Making in Computer-Aided Fault Diagnosis*

As complex systems become more automated, the humans within these systems will come to fill the role of trouble-shooter. This will require that displays and procedures appropriate to that role be developed. However, despite the large body of literature on human problem solving, there is a lack of a fundamental knowledge of human fault diagnosis abilities, especially as these abilities are affected by the availability of various computer aids.

Six experimental studies of human fault diagnosis abilities have been performed [28,29,30,31,32]. The effects of problem size, feedback, redundancy, forced-pacing, computer aiding, and training were studied. The results of these studies were described using two models of human fault diagnosis. One model employs several pattern-evoked heuristics as well as elementary ideas from the theory of fuzzy sets [19,33]. The other model employs a rank-ordered set of rules-of-thumb [34].

Extensions to this work in progress include development of measures of complexity of fault diagnosis tasks [35] as well as evaluation of transfer of training from the troubleshooting simulators to real equipment [36].

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15.8.3 Interactive Modeling of Library Networks*

A queueing network model for analysis of library networks has been developed. It predicts the effects of request routing and document delivery policies on network performance in terms of probability of satisfying a request, average time to satisfy a request, average cost to satisfy a request, and average network processing loads [37,38,39,40].

During the past year, application of the library network model to a case study of the Suburban Library System, an interlibrary loan network which utilizes a particularly high degree of automation, was completed [41]. Further efforts included study of alternative approaches to forecasting the parameters of the library network model [42] as well as extension of the library network model to resource allocation problems [43].

15.8.4 Developing Efforts

Two new topics have been added to our research efforts this year. The first is concerned with developing methods whereby a time-shared computer can monitor the sequence of keystrokes produced by the user of an online editor and, in that way, make inferences about what the user specifically is doing. The goal of this work is to provide methods that would allow editors to "understand" their users [44].

The other new topic concerns training simulators for piloting of supertankers. A simulation is now being developed on a PDP-11/45. When completed, it will be used to study the effects of various cues on human control performance [45].

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16.1 Introduction

During the 1978-1979 time period the Information Retrieval Research Laboratory (IRRL) conducted a number of research and development projects and directed the operation of the University of Illinois' online search service. Major activities included analysis of database data; design of an automatic database selector; design of an integrated man/machine interface to facilitate network resource utilization; provision of computer assistance in development of an index and bibliography of electro-organic synthesis reactions; development of a computer-readable data base directory; and management and direction of the University of Illinois' online search service.

16.2 Analysis of Data Base Data*

The IRRL maintains a body of information about commercially available databases called the Database of Databases. On an NSF contract we studied various statistical characteristics of this population based on the material in our database. Such statistics and analyses are useful both to researchers in the area and to the users and producers of databases.

The particular information developed in the studies performed in the last year considered the age, size, type (scientific, medical, etc.),

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and source (government, private, etc.) of the databases covered. At present 528 databases are covered by our database of databases, but any given study might include only a specified subset of those depending on the needs of the study. The final report to NSF covered 365 databases and was specific to the year 1977. We are currently updating the database to provide those particular data for all databases covered.

The software used in this research consisted of a program framework containing slots into which logic could be inserted to perform specific data selection, cleanup, and analysis. The data was first extracted from the database by our data access program USER and written into a file of (tag, value) pairs. The analysis programs read that file and selected the tags of interest. An effort was made to overlap multiple analyses by re-using data selected and cleaned for prior use.

Cross tabulations were made based on defined groupings or actual values, depending on the data involved. Thus, cross tabulations were done involving both raw year of origin versus grouped size and grouped year of origin versus grouped size. Statistical summaries included means, ranges, and standard deviations of raw data and correlation coefficients between raw data and grouped data. Detection of bad data included identification of records containing illegal or missing values.

The work involved in this project also developed a framework for further studies of the databases available to researchers today. We are currently updating the database and improving the coverage and consistency of data fields that are likely to be important in future studies.

16.3 Automatic Database Selector*

This project evaluated the feasibility of an automatic Database Selector to rank a set of databases according to their applicability to a given user query, based on database vocabulary statistics (Term Occurrence File) modified according to a mathematical model (Term Equivalence Model).

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The Database Selector (DBS) consists of a file containing the vocabulary (with frequencies) from 20 major databases, programs for data management and file generation, programs for query processing, and a mathematical model for normalizing the variability (differing numbers of years worth of files, controlled versus uncontrolled terminology, hierachical and multilevel vocabularies, etc.) found in multiple natural language bibliographic databases.

An operational database selector would be of use to database users, database producers, and database processors. It would help users or searchers allocate resources to searching databases most appropriate to queries. It would help processors and producers carry out database comparisons, vocabulary comparisons, and vocabulary compatibility studies. No merged file of a large number of database vocabularies has been studied before and the number of potential uses of such a file may be considerably larger than those mentioned here.

The major elements of DBS are a master data file called the Term Occurrence File, a software package for file management (file generation, update, delete, etc.) called FIL, a mathematical model for normalizing term occurrence data in various databases called Term Equivalance Model, and a Query Processor to accept queries, match them against the Term Occurrence File, submit term occurrence data to the Term Equivalence Model, and provide histogram rankings of databases as output.

The selection of a file structure for the Term Occurrence File (TOF) was guided by two major objectives. The amount of time needed to search the file for a given term must be minimized, and the file must be as compact as possible, due to the limited availability of online storage space. While the first objective is of primary importance to the success of an operational DBS, since there are a number of ways to organize a file for fast searches, the second objective actually dictated which structure would be used.

The TOF is organized as an indexed sequential file. The terms in the file are kept in lexicographic order according to the EBCDIC collating sequence. Although our machine uses ASCII rather than EBCDIC, we decided to use the EBCDIC sequence because the database vocabulary

tapes supplied to us had the terms sorted according to that sequence. In order to allow for efficient searching, term entries in the file are grouped into fixed length segments, with an index entry generated for each segment. A term can be located by searching the index to determine in which segment it is to be found. That segment can then be accessed directly and searched sequentially for the specified term.

An important aspect of the file structure design is that most operations involved in locating a term take place in main storage. A fast binary search of the segment index determines the segment in which a term occurs. That segment is then brought into main storage and searched sequentially. To simplify this search, term entries are not allowed to cross segment boundaries. This means that there will generally be some unused space at the end of each segment, but the amount of space lost is not signigicant since the size of a file segment is large relative to the size of a term entry. Keeping the index in main storage and reading entire segments of the file into main storage for searching greatly decreases the number of input operations and, therefore, the amount of time needed to search for a term.

The TOF is built by merging a series of files. Since the terms are kept in lexicographic order and the vocabulary tapes are similarly ordered, a straightforward merge can be used to add each database's terms and count information to the file. The merge program converts the terms and counts to the internal format for term entries, groups entries into segments, and generates the segment index as it creates the new file.

The Term Equivalence Model applies various normalizing factors and various weights defined by the system and by the user to a term's frequency of occurence in a database to arrive at a relative measure of the relevance of a given term to a given database.

Normalizations which are applied include: for the length of time which the database covers, for the number of index terms and tokens used in a field, and for the distribution of a term over the databases. User or system supplied weights can be used to adjust the importance of a field in a database.

Terms are combined to form queries using the notions of fuzzy set theory. The association of a term to a field in a given database is described by a value between zero and one (inclusive).

Queries using Boolean <u>and</u> ("*"), and <u>or</u> ("+") are accepted and evaluated and the individual associations of terms with each database and the association of the whole query with each database are returned. The scores for the query are derived from the associations of the individual terms. Since we cannot calculate the occurrence rate for a Boolean combination of terms and then calculate the association, we first calculate the association, then calculate the Boolean combination.

Sets may be assigned names with the assignment operator. Individual terms may be weighted by multiplying them by a constant. Fields may be weighted by assigning the field name a weight. For instance "auth←5" will weight occurrences in the author field 5 times more heavily for every term. Weighting factors can be any real number, including decimals.

The Selector has been implemented and tested on a set of queries, using various combinations of normalization factors and various rules for evaluating Boolean operators in fuzzy logic. The Selector has obtained correlations of around .72 with actual search results in some versions. One version selected the top two databases, as ranked by search results, with precision and recall of .89.

We feel that these results are promising, and that further testing is definitely warranted, to determine the most powerful combination of factors. The effectiveness of the normalizations, in particular, should be tested in an environment in which comparable databases are involved. The testing done in this project was biased somewhat by the data provided and by the differences between the TOF and the databases available for searching.

16.4 An Integrated Man/Machine Interface to Facilitate Network Resource Utilization*

For the first time in history computerized information retrieval is widespread and economically viable. Evidence of this is shown in the volume of machine-readable records, databases, online software packages, vendors, search services, and searches. The major portion of the currently published scientific and technical literature can be identified through computer searches because the references are in computer-readable form. The majority of the world's currently published abstracting and indexing literature is in computer-readable form. There are more than 500 publicly available databases containing approximately 72 million records (citations). Thirty-three million of these records are now available through the various online system vendors in the U.S., Canada, and Europe. Some of the major vendors include: the National Library of Medicine (NLM), Lockheed Information Service (LIS), System Development Corporation (SDC), Bibliographic Retrieval Service (BRS), the Canada Institute for Scientific Information (CISTI), and the European Space Agency (ESA). These online service organizations use a variety of sophisticated online software packages such as ELHILL, DIALOG, ORBIT, STAIRS, CAN-OLE and RECON. Services from the databases, through the online vendors, are provided by dozens of centers, libraries and brokers and they conduct more than 1.2 million retrospective searches per year.

Unfortunately, there are no standards governing the format of databases, the elements and vocabularies included in them, or the online systems for searching them. The lack of standards forces searchers to become familiar with each existing database's coverage and vocabulary and with each system's access protocol, system features, and command language and to keep up-to-date with changes made in all of them.

Many of the differences and variations can be made less apparent by developing translators or tranducers for converting the procedures, conventions, and terminology of one system into equivalent procedures,

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conventions, and terminology of other systems. These converters would make systems appear alike to the searcher and make data bases function as if they used the same vocabulary. Such aids would make the differences transparent to the users thus, they can be called Transparency Aids. An integrated collection of transparency aids can be said to comprise a Transparent System. The aids then are the Transparency Subsystems.

With the reduction of differences the data bases and systems become easier to use; the searching environment becomes more user-oriented. In a more user-oriented environment the requirement for intermediary searchers decreases and we begin to approach the day when most searching will be done by end users (those that pose the search questions).

This research program aims to increase the transparency of retrieval steps by making the discreteness of separate tasks less obvious and by making the variety of system and data base differences less obvious. Specific research tasks include: (1) design of a generalized model for a Transparent System, (2) analysis of the alternative factors affecting the Transparency Interface, (3) development of a skeletal user-oriented terminal, and (4) integration of Transparency Subsystems.

The Transparent System is comprised of: user interface programs; command languages used by the Transparent System; transparency aids performing various functions, such as conversion of command languages or selection of data bases; data files containing descriptive and statistical data about data bases; the connections to data bases and network resources. The model of the Transparent System lays out the relationships among these elements. The alternatives study explores advantages and disadvantages of various model configurations. Development of a prototype user-oriented terminal and integration of some prototype subsystems demonstrates the advantages of a Transparent System by showing how subsystems can interact in performing their functions.

16.5 Swann Bibliography of Electroorganic Synthesis Reactions 1801-1975*

Staff at the Information Retrieval Research Lab (IRRL) are collaborating with a group in the Department of Chemical Engineering (under Professor Richard Alkire, P.I.) to compile and index the Swann Bibliography of Electroorganic Synthesis Reactions, 1801-1975. Financial support for indexing the bibliography came from ERDA, the Electrochemical Society and nine chemical companies.

Approximately 14,000 citations involving electrosynthesis reactions, including original scientific publications, patents, reviews, books, lab manuals and dissertations have been compiled by Dr. S. Swann, Department of Chemical Engineering, University of Illinois during the past fifty years. These citations provided the raw data for the bibliography.

Methodology

(1) Literature Searching

When available the abstracts for the citations were examined and abstracted from Chemical Abstracts or Dissertation Abstracts.

(2) Coding Reactions

Synthetic reactions appearing in the abstracts were then analyzed and coded according to a scheme that described the major types of electroorganic synthetic reactions. The compounds synthesized were named according to CA nomenclature and their molecular formulas determined. Common or trivial names were also provided. One staff member from IRRL participated in this portion of the project.

(3) Computer Generation of the Bibliography

The computer generation of this bibliography was carried out at IRRL under the direction of Professor Martha E. Williams.

a. Data Entry Form

A data entry form was designed with tags for the following data elements:

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*This work was partially supported by the Energy Research and Development Administration under Contract: U.S. Argonne NL 31-109-38-4003 and 9 chemical companies.

i. Type of publication
ii. Reaction class
iii. Class of book
iv. Authors
v. Publication year
vi. CA(Chemical Abstracts) number
vii. Journal citation
viii. Title
ix. Translated title
x. Notes (includes molecular formulas, product names, synonyms)

Data that had been analyzed and coded was transcribed onto the data entry forms by students. Proofreading strategies were established to avoid errors. The forms were then sent to be keypunched and verified.

b. Software Requirements and Implementation

The project required software to build and maintain the data base of bibliographic citations/and to generate the citation listing and various indexes from it. A review of the requirements and budget led to a fairly simple data base design, allowing file maintenance to be done using the time sharing system text editor, rather than a special purpose editing program. Programs were built to check the format and content of the input data, to generate a formatted data base file from the input data, to generate the citation listing in the desired format, and to generate the desired indexes to the citation listing. A utility program was also written to read input data from magnetic tapes. The programs were written for the CSL DEC system-10, using the SAIL programming language, an ALGOL derived language suitable for writing well-structured programs.

The format checking program (FORMAT.SAI) verifies the presence of required data elements in the expected places, checks the validity of certain fields by comparison to tables of acceptable values, checks for sequencing of input items for each record, and flags errors or possible errors in a formatted listing for manual verification. This program is a

straightforward line by line check of the input file, subjecting each line to a sequence of tests determined by the type of line read and expected.

After the citations have been edited to correct errors found by FORMAT, they are formatted by the program CITFMT.SAI. This formatting consists of taking the raw input lines and attaching a sortkey based on the reaction under which the citation is to be listed, sorting, and adding an initial line to each citation containing descriptive information.

If the new batch is to be added to a combined file the program CITMRG.SAI is used to perform the merge based on the previously assigned sortkey.

When a batch or a combined file is ready for printing the program CITPRO.SAI is used to generate the citation listing and index files. CITPRO performs conversions of citation numbers to listing numbers and generates a citation listing structured by type of citation and reaction class described. The appropriate fields are extracted and transformed to suitable index entries, then written to specific index files for subsequent sorting and listing. The indexes generated are selected by the user.

c. Editing

Printouts of the citations and indices were proofread and edited online using the DECsystem-10 editor, SOS.

Organization of the Bibliography

The bibliography is arranged with citations grouped according to the nature of the chemical reaction reported. Within each reaction category citations are arranged according to type of publication and within these subcategories citations are listed in chronological order by year.

Access to the bibliography is provided by four indices:

i. Author Index
ii. Product Name Index
iii. Product Molecular Formula Index
iv. Product Synonym/Common Name Index

Publication

The bibliography will be published under the auspices of The

Electrochemical Society. Publication in the form of a computer typeset hard-bound book is anticipated by late 1979. A computer tape of the citations and indices will also be available at that time.

16.6 Directory of Computer-Readable Bibliographic Databases*

The Computer-Readable Bibliographic Databases--A Directory and Data Sourcebook, compiled and edited by Professor Martha E. Williams and Sandra Rouse, was published in 1976 by the American Society for Information Science. Updates to the Directory were issued in April 1977 and April 1978. A new directory including data that is relevant as of December 1978 is planned for publication in autumn 1979. Unlike its predecessor, the new directory will be published in bound rather than looseleaf form. The computer generation of the printed product is supported by the American Society for Information Science.

Data Collection

(1) Database processors in Europe and North America were contacted by mail for information on the databases they provided access to.

(2) The 13 page questionnaire designed for the first directory was revised to achieve a more consistent format and expanded to include non-US data. For the first time a turn-around questionnaire was computer-generated, containing the information in our files for the data bases covered by the first directory. Existing data entries need only to be verified or changed and missing information supplied by the database producer.

(3) The questionnaires were mailed to the database producers and US and Canadian producers were subsequently contacted by telephone for verification of the data and assistance with questions they may have.

(4) Information on the availability of new databases was obtained from the published literature and contacts with database processors/producers. The producers of new databases were interviewed first by phone. The completed questionnaire was then mailed to

*This work is partially supported by the American Society for Information Science.

them for verification and if necessary followed up by telephone. Only online databases that were publicly available were treated fully. Databases available for internal use only or which are only accessible offline will be listed separately.

(5) Returned questionnaires were checked and data entries standardized.

Data Entry

(1) Data were entered online into the database of databases file using the DBIN program.

(2) Data entries were printed out, verified, and corrected and edited as necessary using the DBEDIT program.

Organization

The directory is organized alphabetically by database name and includes an introduction and four indexes: Subject Index, Database Name/Acronym/Synonym Index, Producer Index and Processor Index.

Information on each database follows the general format:

(1) Basic Information
(2) Producer/Distributor/Generator Information
(3) Availability and Charges for Database Tapes
(4) Subject Matter and Scope of Data on Tape
(5) Subject Analysis/Indexing Data
(6) Data Elements Present on Tape
(7) Database Services Offered
(8) User Aids Available.

16.7 University of Illinois Online Search Service*

During the past year, the University of Illinois Online Search Service, under the general supervision and coordination of IRRL, expanded its services to the students, faculty and staff of the University. In cooperation with the University Library, searching is now available at 10 different locations around the campus, with further growth pending. One additional location, the University Library School, uses the systems available through the search service for classroom use only. Locations

*This work was supported by the State of Illinois.

where searching is offered to University students, faculty and staff include IRRL, Reference Room of the Main Library, Chemistry Library, Biology Library, Labor and Industrial Relations Library, Education and Social Sciences Library, Agriculture Library, Natural History Survey Library, Physics Library, and Veterinary Medicine Library.

Online systems available through the Search Service include Lockheed's DIALOG, System Development Corporation's ORBIT, the Bibliographic Retrieval Service system and the Times Information Bank Individual databases available from these systems total 108.

Use of all systems during FY 79 is given in the following table. The costs given represent the total amount paid by the University to the online vendors concerned. Approximately 50% of this was recovered from the users of the Search Service through the charging of fees.

USE OF ALL SYSTEMS FY79

System	Hours	Cost
BRS	667.58	$17,734.37
LRS	33.69	3,312.95
SDC	7.43	765.64
NYT (partial)	5.47	605.83
TOTAL	714.17	$22,418.79

The total connect hours used represent more than 1500 individual searches, a search being defined as a single session at the terminal, regardless of the number of databases or systems accessed. Of these, approximately half were conducted and paid for, at least in part, by University faculty, students or staff. The remainder were conducted by IRRL or Library staff for internal use. The bulk of these were conducted by Library staff either as practice as they learned to use the system or for general reference or verification work.

Beyond providing general direction and coordination, IRRL performs the following specific tasks related to the Online Search Service: negotiation of contracts with online vendors; training of new searchers; consultation on system problems or difficult searches; promoting the service to the University community through brochures, posters and demonstrations; keeping statistics on all aspects of the Search Service; accounting

work associated with collecting fees and paying bills. We also are developing an automated accounting system to keep track of usage, summarize the costs of this operation, and generate bills and statements.

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17.1 Data Compression and Information Transmission*

The focus of our data compression research during the past year has been on construction of efficient universal variable-rate source codes and bounds on the redundancy of universal variable-rate data compression schemes. Preliminary results on these two topics have been reported in [1] and [2]. New asymptotically tight upper and lower bounds on the minimax redundancy have been obtained for the class of all binary memoryless sources [2]. All of our lower bounds on minimax redundancy R_N^+ for variable-length encoding of blocks of length N are of the form

$$R_N^+ \geq \frac{\log \sqrt{N}}{N} - \frac{c}{N} .$$

In one approach we lower bound this redundancy by a rate-distortion function, which is in turn bounded using the Shannon lower bound. With a uniform density on the unknown parameter (in this case the unknown parameter is the probability of a 1), the constant c that is obtained is $c = 0.5 \log(\pi e/3)$. Using more specialized arguments, some improvements on this constant have been achieved.

We have investigated several specific source codes including the

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composite codes of [1] and codes derived from a particular mixture probability distribution. The redundancies of these data compression schemes have been compared with the above-mentioned lower bound, and the results will be presented in a forthcoming paper.

Further work on this topic is in progress including possible extensions of the results to Markov sources. In principle at least, the composite source coding approach will work for Markov sources as well as for memoryless sources.

Research has also begun on the problem of universal data compression for sources with side information. Here the problem is that not only is there uncertainty in the source output probability distribution, there is also uncertainty in the probability distribution of the side information.

17.2 Robust Digital Detection and Estimation*

The past year's progress in this area can be divided into four major projects, the first dealing with a number of aspects of the digitization of signal detection systems, the second dealing with the design of robust detection and filtering systems, the third considering the problem of state estimation in uncertain systems, and the fourth dealing with state estimation for linear systems driven simultaneously by Wiener and Poisson processes. Progress in these areas involves both the continuation of earlier studies and the development of new projects as described in the following paragraphs.

17.2.1 Digital Signal-Detection Systems

Progress on this aspect of the research has included studies of several aspects of the optimal design and performance analysis of digital (or discretized) signal-detection systems. Specifically, further results have been obtained in an ongoing study of quantization techniques for detection/decision data. Analytical results have been obtained which

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establish an equivalence between optimal quantization for detection systems and a minimum-distortion quantization criterion [3]. Also, an extensive numerical and analytical study of the design and performance of quantizers for use in stochastic signal detection systems has been completed for a wide class of noise models [4] with the conclusion that the performance of such systems can be enhanced considerably by the application of the new design techniques. Further work in this area includes a study of optimization properties related to quantizer design for detection systems [5].

Another effort in this general area has been an investigation of the performance of discrete detection systems which utilize random quantization and/or dither signals as robustifying mechanisms. In particular, randomized and dithered versions of several traditional robust and nonparametric detection systems have been investigated for improved robustness properties. An extensive study [6] indicates that the success of such techniques is highly situation dependent, resulting in considerable performance improvement for some severe types of noise environments while generating poor performance for some other types of noise.

A further aspect of this study includes the development and analysis of algorithms for the adaptation of digitized detection systems to the noise environment. In particular several successful adaptation schemes for the parameters of detection quantizers have been developed. These algorithms are based primarily on stochastic approximation techniques and their convergence has been verified via simulation. A report outlining these results is forthcoming.

Another consideration which arises in the design of digital detection systems is the problem of constrained memory length. Within this context, a number of results have been obtained in an ongoing study of memoryless detection and decision systems for dependent data. In particular, it has been shown that optimum memoryless detection systems can be specified (for a general formulation) by a decision statistic which solves a linear operator equation determined from the second-order statistics of the data [7]. These new results are generalizations of the results of [8]. Further work in this area includes the development of a first-order analysis for treating weak-dependence situations [9] and a study combining both quantization and memory constraints in detector

design. Papers describing these results are currently undergoing review.

17.2.2 Robust Detection and Filtering

A robust system is one whose performance does not deteriorate drastically in the presence of deviations from an assumed statistical model. Several robust detection and filtering problems have been considered during the past year. In particular, robust designs for stochastic-signal detection systems have been studied as reported in [10,11]. Also, for a previously established distance-based formulation of robustness in hypothesis testing, a result has been proven which guarantees the existence of robust systems within very general conditions. Further work in this area includes the application of the first-order weak-dependence analysis discussed in 17.2.1 to design robust detection systems for dependent sampling situations [9]. In the area of robust filtering, formulations have been studied in [12,13] for the problem of Wiener filtering in the presence of spectral uncertainty, and in [14] for the problem of matched filtering in the presence of noise-spectral and signal uncertainty. Solutions for both of these filtering problems have been obtained for several general types of spectral and signal uncertainty classes as reported in [12,14].

17.2.3 State Estimation Schemes for Uncertain Systems

This work involves the use of combined detection-estimation schemes for state estimation in dynamical stochastic systems with uncertainties. Uncertainties are modeled in several different ways. One type of uncertainty model applies to linear stochastic systems with unknown noise covariances. Here, information regarding unknown parameters is assumed to be available in the form of single or multiple bounds on the values of unknown parameters. A weighted minimax mean-squared error cost structure has been applied in deriving the estimator in this case. Another type of uncertainty model is for systems with unknown parameters which may be assumed to be elements of some compact (or convex) space. For this model, an incremental mean-squared error (IMSE) performance criterion is best applied and leads to a minimax state estimator which can be represented as a combined detector-estimator structure. These results have been applied to the problem of state estimation for singularly

perturbed systems with unknown perturbation parameter. Another aspect of this area of research involves state estimation for systems with uncertain time-varying jump parameters. Such parameters are modeled as finite-state Markov chains with possibly unknown transition matrices. For this case it has been found that the Bayes optimal (MMSE) solution can be obtained in recursive form but requires large storage and computation capability. Thus several suboptimal algorithms have been proposed to alleviate this problem and it has been found that a detection-estimation scheme is a tractable approximation to the optimal (MMSE) estimator. In all cases of this phase of research it is seen that detection-estimation schemes exhibit a certain degree of adaptivity for large observation records while maintaining desirable small-sample properties. These aspects of the research are summarized in [15] and further details of this work may be found in [16-22].

A second aspect of this research considers the problem of state estimation for the slow modes of hierarchical singularly perturbed linear stochastic systems. For this problem a reduced-order detection-estimation approach has been derived which produces near-optimal estimates in the presence of multiple perturbation parameter uncertainties. It has been shown that the proposed scheme is of most value when the estimation problem is one of a steady-state nature. However small-sample (i.e. - transient) performance has also been derived analytically for the proposed filter. It has also been shown that the proposed algorithm always contains a near-optimal filter corresponding to the unknown system perturbation parameters and thus questions of convergence need not be considered. A related problem which has also been considered here is that of obtaining a steady-state slow mode estimate for situations in which the perturbation parameter is not small. It has been shown that in many such cases, a near-optimal solution exists that is easily implementable and whose performance is superior to the reduced-order filter without a corresponding increase in complexity. Summaries of aspects of this work can be found in [23-26].

17.2.4 State Estimation for Linear Systems Driven Simultaneously by Wiener and Poisson Processes

In this aspect of the research, the problem of state estimation

in linear stochastic systems driven simultaneously by Wiener and Poisson processes is considered. The emphasis is on the case in which the incident rate of the Poisson driving process is low. The minimum-mean-squared-error (MMSE) filtering equations have been derived for such situations via the Doleans-Dade and Meyer differentiation rule for discontinuous semimartingales and the corresponding basic filtering theorem for white Gaussian observation noise. These optimal filters have been shown to be solutions to nonclosed sequences of differential equations. A performance analysis of such filters and of optimal linear filters for the low-incident-rate case leads to the conclusion that causal filters and linear noncausal filters are inherently unsuitable for state estimation in this class of systems. Because of this unsuitability, a noncausal, nonlinear, suboptimal detection-estimation algorithm for state estimation has been developed based on a strategy combining linear conditional estimation with the detection and estimation of the incident times and marks of the Poisson input process. A first-order approximation technique has also been developed to reduce the error propagation effects that result from the sequential structure of the approach. Both analytical and numerical performance analyses of the proposed scheme indicate that, for low Poisson intensity, the proposed suboptimal smoother performs better than both the optimal causal filter and the optimal noncausal linear filter. Details of this work are included in [27,28].

17.3 Multiple-User Digital Communication*

During the past year, we have continued our work on spread-spectrum multiple-access communications systems, spread-spectrum communications via fading channels, and the design and analysis of periodic sequences. Progress in each of these areas will be described in the sections below. In addition, our project on broadcast channels has been completed and the results were published in a recent journal article [29].

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17.3.1 Spread-Spectrum Multiple-Access Communications Systems

We have considered a wide variety of spread-spectrum multiple-access (SSMA) communications systems including binary direct-sequence (or phase-coded) SSMA systems [30-33], quadriphase direct-sequence SSMA systems [34], frequency-hop SSMA systems [35], and hybrid frequency hop/direct-sequence SSMA systems. Various aspects of the performance of these systems have been investigated with a view towards obtaining new aids for the design of SSMA communications systems.

Much of our work on direct-sequence SSMA communications for additive Gaussian noise channels is concerned with obtaining tight bounds and accurate approximations for the average probability of error. In order to be useful for system design applications, such bounds and approximations must be relatively easy to compute. The approximation which is most easily evaluated for binary direct-sequence SSMA systems is [30]

$$P_{e,i} \approx 1 - \Phi(SNR_i)$$

where $P_{e,i}$ is the average error probability for the i-th signal, Φ is the standard (zero mean, unit variance) cumulative Gaussian distribution function, and SNR_i is the average signal-to-noise ratio for the i-th signal as defined in [30, Section IV]. The accuracy of this approximation has been verified in certain cases by comparing it with the moment-space bounds of Yao [36]. However, comparisons obtainable from Yao's bounds are rather limited because of the difficulty in evaluating moment-space bounds, especially in the interesting case where the maximum interference can exceed the desired signal.

Recently, we have obtained new upper and lower bounds on the average error probability which are not as tight as the best of the moment-space bounds, but which are much easier to evaluate. Preliminary results on these bounds are presented in [37] where comparisons of the new bounds and the moment-space bounds are given.

Our work in quadriphase direct-sequence (QDS) SSMA systems has been concerned with the extension of our previous quadriphase system analysis to include offset or staggered quadriphase modulation. Our

previous unified analysis included the two special forms of quadriphase SSMA described in [34], which are QDS/SSMA with orthogonal biphase-coded carriers and QDS/SSMA with orthogonal quadriphase-coded carriers. However, this analysis did not allow for a time offset between the two orthogonal biphase-coded carriers. Such an offset can be employed to give a more nearly constant envelope signal when the data pulses are bandlimited. The incorporation of this offset into the analysis has been accomplished and will be included in a journal article currently in preparation.

Frequency-hop SSMA communications systems are the most commonly suggested alternatives to the direct-sequence systems. However, much less is known about performance measures for frequency-hop SSMA. We have obtained preliminary analytical results on frequency-hop systems which give the receiver output signal-to-noise ratio as a function of certain parameters of the hopping patterns. These results provide a basis for the selection of frequency hopping patterns and for the design of frequency-hop SSMA communications systems.

17.3.2 Spread-Spectrum Communication via Fading Channels

Most of our research in spread-spectrum communication via fading channels is concerned with the performance of biphase direct-sequence SSMA communications for a general class of Rician fading channels [32,38]. Rician fading channels are those for which the channel output consists of a strong stable specular signal plus a faded version of this signal. The Rician channels, which are often referred to as specular-plus-Rayleigh fading channels, are the result of a transmission medium which gives rise to a major stable communication path and a number of additional weaker communication paths. The fading process is modeled as a general wide-sense-stationary uncorrelated scattering process -- a model which is general enough to exhibit both time and frequency selectivity and to impose no restrictions on the fading rate.

The results obtained are expressions for the receiver output signal-to-noise ratio in terms of the signature sequences and the fading process covariance function. Results for time-selective and frequency-selective fading channels are then obtained as special cases. Numerical evaluations are presented for specific examples of these two types of channels [32,38].

17.3.3 Design and Analysis of Periodic Sequences

Investigations in this area have concentrated on the construction of sequences with desirable correlation properties and on bounds for various correlation parameters. The correlation identities developed earlier can be used to construct multi-valued sequences with good correlation properties. Such methods and examples of sequences obtained in this manner are given in [39]. Another technique of sequence construction is to select sequences from suitable cyclic codes. Correlation properties of sequences obtained from irreducible cyclic codes are studied in [40]. Also included in this paper are results on the maximum odd crosscorrelation and odd autocorrelation values for such sequences. A third method of sequence construction is via the Kronecker product operation. It is shown that the introduction of such a substructure does not significantly affect correlation properties if the constituent sequences are chosen carefully. The minor deficiencies introduced are amply compensated for by the remarkable ease of synchronization for such sequences [41].

Several results have been obtained on bounds for correlation parameters. Mean-square values for periodic, aperiodic, and odd correlation functions are considered in [42] and it is shown that trade-offs exist between the mean-square crosscorrelation and autocorrelation achieved by a set of sequences. Mean-square values of the partial correlation functions are obtained in [43]. Curiously, such values depend on the periodic correlation functions only. Bounds on the maximum values of correlation functions are investigated in [44]. Trade-offs are established for maximum values of crosscorrelation and autocorrelation simultaneously achievable, and sets of sequences which are optimal with respect to the bounds are exhibited. Finally, [45] considers correlation properties of m-sequences and Gold sequences and shows that the average behavior of such sequences (obtained by randomly choosing the phases of such sequences) is better than the average behavior of random sequences.

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18.1 Macromodeling and the Analysis of Large-Scale Circuits*

As the size of new circuits and systems increases, the need for developing numerical techniques suitable for computer simulation within reasonable computer storage requirements and execution time has become greater. One approach that may be used to tackle this problem is the use of partitioning or tearing methods. In this approach the circuit is partitioned into subcircuits, each subcircuit is solved separately, and then the subcircuit solutions are combined to obtain the solution of the entire circuit. Partitioning can save on computer storage if identical subcircuits are created and computing time can be considerably reduced if exploited. This is particularly true in digital circuits where most of the circuit is usually latent at a given time point.

Partitioning algorithms that use sparse matrix solution techniques have been derived and investigated [1,2]. These algorithms attempt to reduce computation by exploiting the sparsity of the equations at the subcircuit level as well as at the interconnection level. Our present work in this area includes an investigation into methods of

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detecting and exploiting latency in both the subcircuit and the interconnection equation. The aim is to obtain a solution in reasonable time without the loss of accuracy.

More recent work includes an investigation into the use of partition algorithms for large-change-sensitivity computation. Future work in this area includes the application of partitioning algorithms in various seemingly different, but computationally similar applications, such as tolerance analysis, statistical design, fault analysis, tuning, security assessment, and reliability among others.

In the area of reduced-order modeling or macromodeling, work was completed on the estimation of gate delays in MOS circuits using simplified models [3]. In addition, work was completed on the use of approximating functions for the reduced-order modeling of transfer functions for linear time-invariant systems [4,5].

18.2 Automatic Fault Analysis of Analog Circuits*

The fault analysis of analog circuits is potentially an extremely difficult problem, because the relationship between any response in the circuit and the component values in the circuit is nonlinear even though the circuit components may all be linear elements. However, the fault analysis problem can be greatly simplified under one of the following two conditions: (1) Both the voltages and currents of a component can be measured, or (2) all the nodes in the circuit are accessible. In device testing, a special test fixture is built so that both the voltage and current for the device can be measured and condition (1) is satisfied. However, once the component has been mounted onto a circuit board and connected into the circuit, it is considered impractical to break connections in order to measure currents. Therefore, in the manufacturing

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environment a bed-of-nails approach is used so that all nodes are accessible and either node isolation techniques [6] or large-change-sensitivity expressions [6] can be used to compute the component values. Industry prefers the former approach.

If it is not feasible to measure component current nor all the node voltages, then the fault analysis problem becomes extremely complex. Under such restrictions the simplest solution to the problem is to design the circuit as a collection of functional modules which are functionally testable, that is, a fault in any functional module should affect the output signals of the module but not the input signals. Furthermore, the module should be a replaceable unit. However, if one further demands that the fault be isolated to a particular component or group of components in the functional unit by means of a few test-point measurements, then the fault analysis problem becomes extremely complex. The reasons for the extreme complexity of the problem are two-fold. First, the problem is complicated because it is highly nonlinear when all of the node voltages are not available. Secondly, and more importantly, it is usually not possible to determine the value of all of the components in the functional unit from a few test-point measurements. Thus, one must assume that all of the components are not faulty, but that only a few of the components have caused the fault. Under such an assumption the problem becomes solvable, but it is still an extremely difficult problem for the following two reasons: (1) Even though not all of the components are faulty, we still do not know the precise value of the good components in the circuit. We only know their nominal design values from the manusfacuter, and that if they are "good" components then their actual value lies within some tolerance of the nominal design value. Here we assume that a good component is one that lies within the manufacturer's specifications, and a faulty component is one which does not. However, this is even an oversimplification, because sometimes a circuit may fail to meet performance specifications even though all the components are "good", or a "faulty" component may not necessarily cause the circuit to fail to meet performance specifications. Also, the fault may not be caused by the components, but

it may be in the connectivity of the components (bad solder joint). (2) An even more important reason for the difficulty of the fault analysis problem under the above restrictions is that we do not know the subset of components in which the fault lies. Because of this difficulty it is important to incorporate into the automatic test system as much information as possible with regard to the most likely components to fail. Initially, this information should be based on the lifetime expectancy of each component. This lifetime expectancy should be based on the stress under which the component operates, for example the percentage of maximum allowed power dissipation. However, ideally a test system should contain an adaptive algorithm in which the most likely to fail component data is updated with each maintenance procedure. Such information would be an invaluable asset to any automatic test system.

Now that we have outlined the complexity of isolating component faults from test-point measurements, let us discuss the possible methods that can be used in such an automatic test system. There are basically two methods (1) the fault dictionary, and (2) post-test analysis. In the fault dictionary approach the circuit is simulated for a number of anticipated faults and fault signatures are stored in a dictionary for each type of fault. The automatic test system simply measures the circuit under test and forms a set of fault signatures. These signatures are then correlated with the fault signatures in the dictionary. This method has the advantage of simplicity. Its disadvantages are that one must not only be able to anticipate which faults will occur, but one must also anticipate the values of the faulted components. Secondly, the fault signatures frequently give ambiguous information. For example, a given signature generally corresponds to more than one possible fault condition. The reason for this ambiguity is that it is not possible in the pre-test simulation stage to correctly assume the values of components in the faulted circuit, and it is impossible to simulate the circuit under all possible combinations of element values. Thus, the reliability of this method depends to a large extent on the ability of the test programmer to anticipate the faults that will occur in the operation of the unit, and the choice of test points to minimize ambiguity in the fault signatures.

In post-test analysis one attempts to find the faulty components from the test measurements either by means of a circuit simulator program or by means of large-change-sensitivity equations. For example, in the first case the test system contains a circuit simulator and an adaptive algorithm. The algorithm is usually based on first-order sensitivity or optimization methods. It adjusts the component values in the simulator until a match is found between the simulated circuit and the test circuit. The problem with this approach is that the solution is non-unique and optimization methods tend to stall at local minima. Also, many circuit simulations may be required in order to locate the faulty components. The advantage of this method is that one does not have to anticipate the value of the components in the faulty circuit, although as with the fault dictionary method, prior knowledge about the most likely faults to occur greatly improve the performance of this method.

We are investigating the large-change-sensitivity method [6]. In this method one also attempts to find the faculty components from post-test calculations. However, post-test circuit simulations are not required, because we do not attempt to find the value of the faulty component. Rather we search for an indication as to whether or not a component is causing the fault to occur. This is done by solving a subset of the large-change-sensitivity equations for the possible faults. These equations are linear and their dimension is less than the number of available test-points. This solution is then substituted into the remainder of the large-change-sensitivity equations to determine if the solution also satisfies these equations. If it does, then we have located the potential faulty components. The advantage of this method is that one does not have to anticipate the value of the faulty components as is the case in the fault dictionary method, nor does one have to simulate the circuit iteratively until the simulated circuit results match the test circuit measurements. However, as with both of the above methods, component tolerances can lead to ambiguous results, and again prior knowledge about the most likely faults to occur greatly improve the performance of the method.

In conclusion, let me comment on the areas of investigation which we believe will be the most fruitful. First, with regard to new products, the circuit layouts should be standardized so that the same automatic test equipment can be used even though the same part may be supplied by different manufacturers. Secondly, as much as possible the circuit should be designed as an interconnection of functionally testable modules which can be economically discarded when they become faulty. Finally, new protective coatings should be developed which can be easily stripped from the circuit board so that the bed-of-nails approach used in the manufacturing environment can be applied to military hardware.

With regard to both new equipment and equipment already in the field, the single most important contribution to be made is the development of a systematic procedure to identify the most likely failure modes in a circuit. Initially, such a procedure must be based on device reliability and circuit design data, but an effective algorithm should also include maintenance data as it becomes available. Since it is usually not possible to uniquely identify the faulty components from test-point measurements, such data would greatly improve the reliability of the fault dictionary method and both types of post-test analysis methods. In order to incorporate such data into the test algorithm, the automatic test programmer should work closely with the maintenance personnel for a period of time until reliable data is obtained for the test program.

Another area where improvement is needed is the simulation of analog circuits for different parameter values. Presently, circuit simulation programs completely resolve the circuit equations every time a parameter is modified. Thus, the circuit simulation steps for both the fault dictionary method and the post-test circuit simulation method are not computationally efficient. These methods should use simulation algorithms in which the responses can be updated as simply as possible for a given parameter modification. More effort is needed in this area. We are presently conducting a study in this area.

Finally, we see a need for several different types of benchmark circuits which can be used to compare the three different approaches which we have summarized in this report, the fault dictionary, post-test circuit simulation and our large-change-sensitivity approach.

18.3 Tuning of Analog Filters*

Typically, in the manufacture of electrical filters it is not practical to make components with sufficiently small tolerances in order to achieve one hundred percent yield. Rather it is more cost effective to have less stringent tolerances on the component values and to tune those filters that do not meet the design specifications by adjusting the parameter values of a subset of the components. For example, in the manufacture of hybrid active filters the capacitors are not normally trimmed, so that only the resistors in the circuit can be used to tune the filter. Furthermore, resistor trimming increases the resistance. This restriction requires a very carefully designed tuning scheme. In addition, tuning can be a very expensive process. Therefore, the algorithm should be fast, and it should maximize the yield. In practice there exists some tuning techniques such as (a) functional tuning, (b) deterministic tuning and recently a new technique was proposed by Lopresti [7], (c) linear optimal tuning. All of these techniques have been studied and the advantages and disadvantages of each of them have been investigated.

This research project was started in the belief that the previous work in tuning analog filters could be improved. A new algorithm [8] was sought in which the network function does not need to be computed in symbolic form nor do the coefficient sensitivities need to be computed [7]. The method makes use of the adjoint circuit concept to develop a relationship between large parameter changes and the corresponding voltage changes in the circuit [9]. The voltages in the

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manufactured circuit are measured at a set of critical frequencies and the deviations between these voltages and the corresponding voltages in the nominal circuit design are calculated. The voltage errors are then substituted into the large parameter change expression, and the changes in the tuning elements necessary to reduce these voltage errors to zero are computed by solving a set of linear algebraic equations. Although the voltage deviations between the manufactured circuit and the nominal circuit are not identical to the voltage deviations between the manufactured circuit and the tuned circuit, because only a subset of components are adjusted, experience has shown that this approximation yields an excellent first guess for the parameter changes required to meet the design specifications. Applications of this method for tuning active filters with multi-feedback structures [8] yields a circuit whose response is very close to the desired response even when the manufactured circuit parameter values are quite distant from the nominal design values. Usually one can obtain results that are almost identical to the desired response in only two or three iterations.

Further research is being done on obtaining statistical models for the manufactured circuits. Also the convergence properties of the method are being investigated.

18.4 An Investigation of New Structures for Integrated Sampled-Data Filters*

Switched capacitor (SC) filters have drawn attention from circuit designers because they can be fully integrated using standard MOS processing technology [10]. High quality MOS capacitors, analog switches and operational amplifiers are available as circuit elements in the integration process. In addition, the accuracy of SC filters depends only on capacitor ratios. These ratios can be obtained with an accuracy better than one percent over a wide temperature range in the fabrication processes.

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The design and fabrication of SC ladder filters has been reported in the literature [11]. Since the circuits are derived from doubly terminated LC ladders, they are low sensitivity structures that are expected to produce good yields in the integration process. A study of SC terminations for second and fourth order lowpass SC ladders was conducted. Parallel and series SC terminations were analyzed with a computer analysis program. Results showed that the mismatched terminations cause more degradation in the frequency response of the second order ladders than in the fourth order ladders. For the second and fourth order ladders that were analyzed, the series SC termination better preserved the stopband response than did the parallel termination.

A new filter design technique was developed [12] in which the state equations describing a SC filter are manipulated into a predetermined functional form. A circuit realization of this final functional form contains only Euler integrators. Therefore, it is possible to design a SC filter by applying the bilinear z-transformation to an analog prototype, and then realize the filter with simple Euler building blocks. Although this approach does not result in a minimal number of components, it is a general approach that has been used to realize a biquadratic filter section.

In general, switched capacitor integrator structures are widely used in the design of SC filters. For example, in the design of SC filters from network equations of digital filters Euler integrators combined with capacitor summers are used. In the design of low sensitivity SC ladder filters from analog ladder filters, lossless discrete integrators are used. For circuits consisting of integrators, summers and combined integrator-summers, circuit equations in both the time and frequency domain can be easily formulated. This approach led to the development of a circuit analysis program, SCAP, which performs a time domain or frequency domain analysis, given the topology of the SC circuit [13]. In its present form, SCAP can be used only on circuits that are constructed from SC integrators (and summers) with virtual grounded op amp inputs. However, the formulation is general enough to accommodate the majority of SC circuits of practical interest while providing the advantages of low cost, fast executing speeds, and low memory requirements.

18.5 Simulation of Digital Filter Structures*

This summary describes a computer program for the analysis of digital filter structures [20]. The program is capable of both time-domain and frequency-domain analysis. The program rounds the coefficients to a specified bit length before computing the response of the filter. Thus, the effect of coefficient rounding on the response can be determined. The program will also scale the coefficients using either the L_2 or L_∞ norm in order to avoid overflow in fixed point arithmetic implementations. In addition, the program can compute the coefficient sensitivity and noise variance of the structure. The program is written in FORTRAN for the DEC-10 and HP 2100 computer systems. The user simply describes the structure in terms of multipliers or unit delay elements, the summing nodes to which they are connected, and their values. Sparse matrix techniques are used throughout the program, and adjoint system techniques are used in the sensitivity and noise analysis calculations so that the program is computationally more efficient than other programs. With this program the sensitivity, noise, and limit cycle behavior of several different digital filter structures, including the cascade structure and several low sensitivity structures, such as the wave digital filter structure and other multiple feedback structures, have been computed.

18.6 New Techniques in Digital Signal Processing for Synthetic Aperture Radar†

Synthetic aperture radar is used to produce terrain images from data collected with a sidelooking radar carried on an airplane or space vehicle [14]. Resolution along the range dimension (perpendicular to the flight path) is controlled by conventional methods, e.g., by controlling

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the effective pulse length with linear FM modulation. However, high resolution along the flight path (azimuthal coordinate) is difficult to obtain because a small physical antenna cannot provide the narrow beamwidth necessary for high resolution in this dimension. The synthetic array principle overcomes this difficulty through signal processing techniques.

At regularly spaced positions along the flight path the radar illuminates the ground area to be imaged. The echo returns are demodulated into in-phase and quadrature video components, which are then recorded photographically (film) or electronically (tape, disk, or digital memory). After the recording has been completed at N distinct positions in space, the stored signals are coherently summed to create the equivalence of a long physical array with a narrow beam pattern. The synthetic array principle provides the desired azimuthal resolution at the expense of extensive signal processing. Since the discovery of the FFT algorithm, digital processing of SAR imagery in a real time environment has become a viable alternative to the optical techniques that were used during the past decade [15].

Research has been conducted in two distinct areas of SAR signal processing. The first is an analytical study of signal processing kernels that comprise fundamental SAR image reconstruction techniques. FFT "stretch" algorithms for both rectangular multiple reference function and polar format single reference function processing were analyzed [16,17]. Expressions were derived for returns from an array of point targets, as the sampled waveforms would appear in the baseband recording domain. FFT stretch processing is known to be a suboptimal (approximate) focussing algorithm that causes misregistration and resolution loss for targets near the edges of the illuminated area. The cause of this degradation appears as uncompensated phase terms that can be selectively deleted or included to study their effects. A computer simulation program is now being developed to process the simulated recording in order to study the multiple reference function and polar format FFT techniques.

The second area of SAR research is an investigation of high speed SAR processor designs. Residue number coding has been proposed for implementing real time Doppler prefilters. New results were obtained in designing specialized residue classes that facilitate RNS scaling and error detection/correction in both recursive and nonrecursive digital filters [18,19]. Residue number signal processing techniques appear to be well matched to the high data rate and fault tolerant requirements of a high speed SAR processor.

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19. DECISION AND CONTROL

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19.1 Introduction

Several projects have led to many results involving various aspects of control analysis, synthesis, and optimization. The key directions are in decentralized control of large scale systems; multi-models in large scale systems; structural properties of systems including sensitivity, controllability, and observability; model simplification by singular perturbation methods and chained aggregation methods; stochastic control of systems containing parameter uncertainty; control of systems with multiple decision makers; and optimization methods.

19.2 Sensitivity Adaptive Feedback with Estimation Redistribution*

We have developed recently an approach to the synthesis of dynamic controllers for systems containing unknown random parameters. This approach, called SAFER control, allocates individual parameter estimation costs for a given total parameter estimation cost, so as to minimize the primary control cost function [1,2]. This is achieved by appropriate choice of controller gains from the dynamic controller and choice of weighting coefficients for the sensitivity functions which are

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related to the parameter estimation accuracy. Some simplification can be effected when output sensitivities rather than state sensitivities are used [2]. The general output SAFER problem is still quite complicated and the algorithm is still numerically complicated. Under investigation is a class of single-input single-output discrete-time systems with unknown random parameters. This is the class treated by the theory of self-tuning regulators of Astrom and his group over the past 15 years. Using only a one-step ahead minimum mean square error criterion, as in the self-tuning regulator case, the SAFER algorithm is drastically simplified. Furthermore, the sensitivity adaptation is also over a single stage in the future.

The SAFER concept was applied to a model for a magnetic suspension system to obtain some numerical and simulation experience with the method [3]. It appears that the original SAFER algorithm is relatively too time consuming but perhaps the simplification to the one-step ahead minimization for single-input single output systems might be practical but this has not been tried as yet. The associated on-line estimation via an extended Kalman filter was numerically unsatisfactory but a mathematically equivalent and numerically superior method using matrix factorization improved the numerical stability problem [3].

19.3 Sensitivity Reducing Compensators Using Observers*

We developed the concept of comparison sensitivity for multivariable systems several years ago as a tool for assessing the benefits of feedback [4,5]. Linear optimal state regulators were found by Kreindler to automatically satisfy our sensitivity criterion [6]. Recently Naeije and Bosgra [7] extended Kreindler's result to output feedback controls using dynamic compensators. Implementing a full state feedback law using an observer to estimate the unmeasured states will not satisfy the output sensitivity reduction criterion in general. We have developed

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an extension of Naeije and Bosgra to the particular case of output feedback systems using state observers [8,9]. An interactive software has been developed and applied to a simple aircraft control example [8]. The design procedure using observers is an improvement over the design with arbitrary compensator dynamics for the following reasons. First, the design of the observer is well-known and by placing the poles of the observer the designer is selecting poles of the overall feedback system. Second, the dynamic order of the reduced order observer is less than the maximum found on the dynamic order of the compensator designed by the methods of Naeije and Bosgra. Finally, the use of observers leads to a useful interpretation of the sensitivity weighting matrix [8].

19.4 Design of Optimal Systems with Low Sensitivity to Small Time Delays*

This project is concerned with a study of trajectory sensitivity of optimal control systems. The parameter with respect to which sensitivity is studied is a small undesirable time delay that might occur in a system design nominally with zero delays. Small time delays are usually expected to occur in systems due to several reasons, among which are the effects of mass and/or energy transport and the finite measuring time of the system outputs. These delays are very often neglected. However, they might cause significant deviation from the nominal system trajectory.

We consider the design of optimal control systems in a manner that makes their trajectories insensitive to small time delays. The design strategy is to augment a standard quadratic performance index with a term of sensitivity measure. For deterministic systems the minimization process is carried out using the well-known Minimum Principle. For stochastic systems, the minimization process of the augmented performance index is carried out by transforming the problem into an equivalent static minimization problem. To apply the above methods to our problem

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of interest, we use the notation of a sensitivity function defined as the first partial derivative of the state vector with respect to the delay, evaluated at the nominal value of the delay, i.e. zero. Several cases are considered. The delay is assumed to occur either in the plant or in the feedback path. Several system structures are discussed. For each case, both stochastic and deterministic systems are studied. We applied the proposed design strategy to a practical example. The numerical results are analyzed and we concluded that our design scheme is reliable, especially if we want to reduce sensitivity of system states according to a desired weighting [10].

A similar procedure for a general parameter but for discrete-time systems is reported in [11].

19.5 Output Feedback Compensator Design*

Based on a modified output regulator problem, a design oriented methodology has been developed for the synthesis of output feedback compensators retaining $\ell (1 \leq \ell \leq n)$ optimal eigenvectors from an nth order reference state feedback regulator. Viewing ℓ as a design parameter, Medanic [12] has shown that the case $\ell > r$ leads to a dynamic compensator of dimension $(\ell - r)$ whose parameters can be determined by solution of an associated output feedback pole-placement problem. Using an iterative dyadic pole-placement procedure, an algorithm has been devised recently which determines the solution of this pole-placement problem without _a priori_ assumptions on the compensator dimension. The methodology also can be extended to the class of stabilizable systems and the required compensator shown to possess a separation property. Details of the procedure may be found in [13], C.S.L. Technical Report R-847 (DC-26). A journal article is being prepared for submission.

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19.6 Zeros of Multivariable Systems*

The definition of a zero of a scalar transfer function is well known. Indeed, the properties of zeros are very important for describing the open and closed loop behavior of dynamical systems. There is a natural interest, then, in extending this concept to linear time-invariant multivariable systems. The approach generally taken is to define zeros for multivariable systems so that these zeros retain some property of zeros of a scalar transfer function. As it turns out, the zeros so defined also have other properties which can be considered generalizations from the scalar case, so the generalization is not unique.

Zeros defined for multivariable systems have been of considerable interest recently. For example, zeros play a major role in the construction of minimal order inverse systems, the construction of reduced order models, decoupling theory, and servomechanism design. They also have been used in relating the structure and coefficients of the quadratic weighting matrices to the resulting eigenstructure of the optimal state regulator and in the stability of the optimal state regulator using high gain feedback.

An in-depth survey of the existing literature on zeros has been made [14]. Representation of a multivariable system can take three forms: the transfer function matrix, state space system in the time domain, and state space system in the frequency domain. Correspondingly, the definitions of zeros have been extended to each of these representations. In [14] these definitions are reviewed and their interrelationships are explored. This includes the relationship between different definitions of zeros for the same system representation and the interrelationship of zeros defined for different system representations.

Once zeros are defined, it is of interest to develop algorithms for their efficient calculation. As it turns out, neither the basic definitions nor their elementary properties are well suited to either hand

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or computer calculation. Therefore, properties were explored which lead to algorithms for computing zeros. Several algorithms for calculating zeros have appeared in the literature. A brief review of the algorithms is included in [14]. Finally, a new algorithm based on the geometrical properties of linear time-invariant systems has been developed. Details are presented in [14], along with several examples which illustrate the method. A journal article is being prepared for submission.

19.7 A Newton-Lyapunov Design for a Class of Nonlinear Regulator Problems*

In contrast to the well-developed theory of the linear regulator problem, there are relatively few results on the nonlinear regulator problem. The main difficulty lies in solving the Hamilton-Jacobi equation arising in such problems for the optimal feedback control. In previous work, based on the assumptions that the nonlinearities are weak and the linearized problem is controllable (stabilizable) and observable (detectable), feedback controls are obtained using matched asymptotic expansions. Numerical computation of the series expansions involves tensor equations, and the domain of stability depends on the truncation of the series expansion of the control.

We have extended some results from linear regulators to a class of nonlinear regulators using an iterative scheme. In particular, we obtain analogs of the stabilizing solution to the Riccati equation and the Newton-Lyapunov method for computing the Riccati solution in nonlinear regulators. The iterative scheme differs from earlier ones in that it successively generates improving controls while maintaining a fixed domain of stability. Exponential stability which is crucial in previous work is not essential here.

We consider a class of nonlinear regulators where the system is linear in the control and the cost function to be minimized is a quadratic form of the control. Due to the structure of the problem, the Hamilton-

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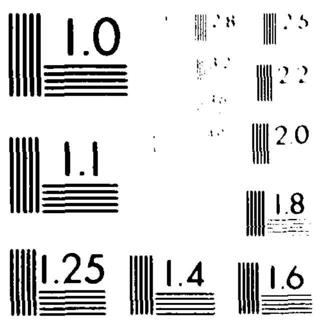

MICROCOPY RESOLUTION TEST CHART

Jacobi (H-J) equation yields a feedback control law with a simple structure. We have shown that the stabilizing solution of the H-J equation is the unique optimal solution. At each stage of the iteration, we improve the feedback control which possesses a domain of stability not smaller than that of the initiating control. The controls are successively solved for from a system of linear partial differential equations, which is an analog of the matrix Lyapunov equation appearing in the iterative solution of the Riccati equation for linear regulators. Furthermore, the improvement in the cost function is quadratic. The uniqueness result guarantees that if convergence occurs, the design method yields the optimal solution.

The numerical solution to the partial differential equations is computed using the method of characteristics which deals with an equivalent system of ordinary differential equations. The result is a feedback control map. In practice, to reduce the amount of data storage and computation, suboptimal schemes such as polynomial approximations, can be used. Further details are given in [15].

19.8 Variable Structure Model Following Control Systems*

A new design concept for adaptive model-following control systems capable of shaping the error transient responses is developed using the theory of variable structure systems and sliding mode. It is shown that the resulting model-following control system exhibits adaptive properties inherent in adaptive model-following systems designed by existing methods. An aircraft control problem which has been approached using various model-following techniques is considered and a performance comparison with the present design is made.

The direct application of linear optimal control theory to the design of multivariable control systems often encounters two main difficulties in practice. First, it is difficult to specify in terms of a

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performance index the design objectives. One of the most efficient methods to avoid this difficulty is to use the so-called "linear model-following control systems" (LMFC). The idea is to use a model, which specifies the design objectives, as a part of the control system. The objective of the controller synthesis is then to minimize the error between the states of the model and the controlled plant. On the other hand, large variations of plant parameters often occur. This second difficulty is also encountered by LMFC. The analysis of the performance of various LMFC systems designs, leads to the development of the so-called "adaptive model-following control systems"(AMFC) which is capable of retaining high performance in the presence of parameter variations.

In general there are two classes of design methods of AMFC systems. Landau based his method on the hyperstability concept proposed by Popov. Other designs utilize Lyapunov methods. While the primary concern of these design methods is to guarantee that the error between the states of the model and the controlled plant goes to zero, the transient behavior of this error is not prescribed. Only some qualitative discussions are provided on the relationship between the adaptation gains and the speed of the norm of this error.

The adaptive control laws derived using the Lyapunov method for single-input-single-output model reference adaptive systems are discontinuous control laws. These control laws belong to a particular class of discontinuous feedback laws called variable structure systems (VSS). The salient feature of VSS is that the so-called sliding mode exists on a switching surface. While in sliding mode, the feedback system becomes less sensitive to system parameter variations and disturbance inputs. The theory of VSS has been developed in the U.S.S.R. in the last fifteen years. The advantage of designing AMFC systems by the theory of VSS is that the transient response of the model plant error can be prescribed by the design. We have developed a design procedure for multi-input model-following systems which retains the error transient shaping capability as in the single-input design by utilizing design methods for VSS. We have applied this method to an aircraft control problem.

The plant of this problem represents the three degrees-of-

freedom linearized longitudinal state equations of a conventional subsonic aircraft, a Convair C-131B. The model in this case is chosen to be the estimated dynamics of a large supersonic aircraft. This problem has been considered in various model-following papers, and it was used in comparing the performance of VSMFC systems to AMFC systems and LMFC systems. Simulations indicate that a variable structure model-following control law significantly improves the error transient behavior in comparison to that for an adaptive model-following control or a linear model-following control. Details are given in [16].

19.9 Leader-Follower Strategies*

The optimization of multiple performance criteria for dynamic systems with multiple control authorities differs in a fundamental way from the optimization of a single performance criterion for a dynamic system with a single control authority or decision maker. This difference is in the need to adopt a solution concept. In this project two solution concepts have been investigated. One is called the leader-follower strategy concept whose development for dynamic systems we have pioneered. Another is called the Nash strategy concept which is appropriate when all decision makers choose their strategies simultaneously.

The basic concept for leader-follower strategies in a dynamic system with two decision makers is based on the assumption that the decision makers choose and announce their strategies sequentially, i.e., the strategy of one decision maker, called the leader, is known to the other, called the follower, before the follower chooses his strategy. Moreover, the information structure is specified before strategies are selected. Three information structures are investigated. The first is open-loop where only the initial state is known to both decision makers. The second information structure considered permits measurement of the present state by both decision makers but no memory is allowed so that past values of

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the state are not remembered. The third information structure allows both decision makers to have memory. We have shown earlier that the leader-follower strategies are generally different for different information structures. Furthermore, the principle of optimality does not hold in general. The derivation of necessary conditions for the closed loop case remained elusive until very recently. A survey of results available as of 1978 is in [17] while [18-31] give the original sources and further details. Necessary conditions for a linear closed-loop leader-follower strategy when the initial state is random and uniformly distributed on the unit sphere are derived in [24]. A successful derivation of necessary conditions for closed-loop leader-follower strategies, a problem which remained unsolved for six years, is in [25]. Closed-loop leader-follower strategies when the information structure allows knowledge of past values of the state are developed in [26]. Furthermore, [26] shows conditions under which the leader-follower strategy coincides with the desirable team solution for the leader whereby all decision makers optimize the objective function of the leader.

19.10 Existence and Well-Posedness of Optimal Strategies*

Sufficient conditions for the existence of solutions for Nash strategies when the system is linear, the objective functions are quadratic, and the strategies are constrained to be linear functions of the state are reported in [32,33]. When the system matrices are analytic functions of time, it is no longer necessary to constrain the strategies to be linear. The linear strategies are the unique analytic solutions to the closed-loop Nash problem. This is described in [34]. A series expansion for a parametric dependence of a Nash strategy is described in [35]. An interesting example of the detrimental effect of more information in a Nash situation is given in [36].

Using concepts of leader-follower strategy and Nash strategy we

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examine the impact of singularly perturbed reduced order models in the determination of simplified strategies. The principal question here is that of well-posedness, that is, the identity of the limit of the performance using the exact strategies, to the limit of the performance using the simplified strategies. In contrast to optimal control problems, the multicriteria multiple decision maker problems could lead to ill-posed simplifications. In [37-44] we have demonstrated by simple examples, that the natural singular perturbation order reduction for nonzero-sum Nash problems could lead to ill-posed strategy simplifications. We show under what conditions the natural order reduction would lead to well-posed simplifications. We also offer alternative strategy simplifications which are well-posed in those cases where the natural simplification would be ill-posed. The results demonstrate that the usual model simplification widely used in control should not be automatically used for problems with multiple decision makers.

19.11 Constrained Stochastic Power Flow Analysis*

The effective analysis of power systems requires the evaluation of system response for all possible levels of loading. The random nature of station loads due to cyclic loading or forecast uncertainty creates an equivalent set of random variations in bus voltages and line power flows. The nonlinearity of load flow methods prohibits the direct computation of these variations. In this research, the nonlinearities are divided into two classifications, continuous and discrete. The continuous nonlinearities arise from the product of voltage and current conjugate in fixed power representations. The discrete nonlinearities arise from the constraints on control variables. The effects of the continuous nonlinearities can be considered by linearizing the load flow equations around the mean load operating point [45,46]. The inadequacies of such a linearization are being investigated [47,48]. Multiple linearizations are being considered for analysis involving discrete nonlinearities. This approach is being tested utilizing various load representations [49].

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The constrained stochastic power flow problem is aggravated by the large scale property of typical power systems. Work in the area of "Statistical Equivalents" has recently been initiated to overcome certain limitations caused by the large scale property. The objective of this research is to obtain a reduced set of representative nodes which adequately describe the statistical behavior of a larger power system under random load variation. Initial work in this area has considered the identification of statistically correlated nodes or lines from a structural basis and from a load or source basis.

19.12 Functional and Path Reproducibility*

When can a rocket be made to follow a desired path, with prescribed velocity? Put more generally, when can the control system described by

$$\dot{x} = f(x,u,t) \tag{1}$$

be made to yield a given output

$$y = g(x,u,t) \tag{2}$$

where u(t) is a member of a set of specified controls?

Questions of this sort have been studied for about the past fifteen years, with greatest attention devoted to the linear time invariant case

$$\dot{x} = Ax + Bu \tag{3}$$

$$y = Cx + Du \tag{4}$$

many treatments considering only the output equation

$$y = Cx. \tag{5}$$

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We have studied the system (1), (2), and the time varying system obtained by linearizing about a given trajectory

$$\dot{x} = A(t)x + B(t)u \tag{6}$$

$$y = C(t)x + D(t)u \tag{7}$$

and obtained results which are, we believe, new.

We have also studied the problem of path reproducibility, namely when can a given geometric path be followed, with a range of velocities. This can be reformulated as a study of (1) and (2) subject to a reparametrization of the independent variable, t, the time. Again we have obtained sufficient conditions for path reproducibility.

This work, which is being prepared for publication, has been done by Prof. N. Wax in collaboration with Prof. F. Albrecht, and Dr. K. Grasse, of the Mathematics Dept., U. of I.

19.13 Phase Locked Loops*

One of the most useful, and currently ubiquitous, of nonlinear feedback circuits, is the phase locked loop. The phase locked loop (PLL) used in applications as varied as spacecraft communication and motor speed control, has been studied intensively. Most treatments linearize about an assumed solution, and consider only a few stages of filtering.

We have succeeded in formulating the description of the PLL in general assuming only that the filtering is done in a finite number of stages, and that the filter is stable. It is then possible to use one of the standard methods of nonlinear analysis, the method of averaging, to obtain results. This we have done, and work is continuing on this problem.

This work is being done by Prof. N. Wax in collaboration with Prof. P. J. Ponzo, Associate Dean, Faculty of Mathematics, University of Waterloo.

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19.14 Local Analysis of Hierarchical Control Algorithms*

The topic of hierarchical control has developed into an important area of large scale systems theory over the past two decades. The development of the basic algorithms of hierarchical control was strongly motivated by the success of decomposition algorithms in nonlinear programming. Although the terminology and algorithms have been extrapolated to a considerable extent, the key ideas of decomposition and coordination remain central to the theory [50].

Due to the mathematical programming origins of hierarchical control theory, most analyses of algorithms are concerned with global convergence behavior. Although very important, such analyses have been unable to investigate the relationships between algorithms and compare their behavior. Also, a major class of control algorithms [51,52]which can be solved in a hierarchical manner does not fit the optimization framework for which these analyses are applicable.

In an attempt to fill these gaps in existing hierarchical systems theory, a new framework for analyzing hierarchical algorithms has been developed [53]. The framework views each hierarchical algorithm as an iterative procedure for the solution of a set of nonlinear equations which describe the control problem. This viewpoint allows the introduction of several powerful results and concepts from numerical analysis to the analysis of hierarchical algorithms. As a result, it is now possible to compare both the structure and local convergence rate of individual hierarchical algorithms. Such a study was performed for four currently popular hierarchical algorithms [54]. The theory has also been used to demonstrate a slow convergence rate for the goal coordination algorithm [55].

Current research topics center on the application of this formulation to problems for which the decomposition is not exact. Specifically, we consider problems which are first decomposed exactly. The subproblems are then formulated as approximations to the problems resulting from the exact decomposition. Such situations arise when some

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sort of aggregation (e.g. modal, multiple time scale, etc) is used to simplify any of the problems. These situations fit naturally into the local analysis formulation.

19.15 Output Feedback Design*

A new approach to output regulator design has been developed. Methods are proposed for construction of static and dynamic output regulators based on projective controls which can be realized using available outputs. They retain in the resulting closed-loop system an invariant subspace of the state feedback solution (which defines the desired transient dynamics of the system). Low order dynamic regulators are introduced to increase the dimension of this invariant subspace and to enable the shaping of the entire spectrum of the closed-loop system. A three-part design oriented methodology is developed for construction of low order regulators. The procedure terminated with the minimal order of the dynamic controller that insures satisfactory spectral characteristics of the system. For every order and for the corresponding controller parameters the feedback gains are a realization of projective controls and thus satisfy the relevant optimality condition. The results on the design of static and dynamic regulators for centralized control problems are presented in [56,12]. Extensions to the decentralized case are presented in [57].

A closely related study[58] provides new results on the existence of equilibrium solutions of the general Riccati matrix differential equation, including local stability properties and regions of convergence to the unique stable equilibrium. These results follow from new geometrical properties and regions of convergence to the unique stable equilibrium. These results follow from new geometrical properties of equilibrium solutions and their use in the characterization of linear and nonlinear manifolds of the Riccati matrix differential equation.

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19.16 Parameter-space Design of Robust Control Systems*

Most existing methods for the design of robust control systems try to achieve robustness of a system property, like stability, with respect to small perturbations of plant parameters in unknown or conveniently analyzable directions (e.g. gain or phase variations). Such methods lead to conservative results when applied to problems with large perturbations in known directions, e.g. for a crane with widely varying load mass and rope length or for an aircraft with widely varying altitudes and speeds. Let the plant model in sensor coordinates

$$\dot{x} = A(\theta)x + B(\theta)u$$

be given for several typical values of the physical parameter vector θ, i.e. $A_j = A(\theta_j)$, $B_j = B(\theta_j)$, $j = 1, 2, \ldots J$. A fixed state feedback gain K is sought, such that all eigenvalues $\lambda\ (A_j - B_jK)$ are located in specified regions Γ_j in the λ-plane.

Other large perturbations in known directions are sensor or actuator failures and combinations thereof - leading to "crippled" K matrices K_m, $m = 1, 2, \ldots M$, in which some rows and columns of K become zero. K should be designed such that all roots of

$$\prod_{m=1}^{M} \prod_{j=1}^{J} \det\ (\lambda I - A_j + B_jK_m)$$

are located inside an emergency region Γ_E in the λ-plane.

A new tool for tackling these problems is proposed [59]. The basic idea is to map boundaries of λ-plane regions into boundaries in the parameter space K of feedback gains by a modified pole placement method. Intersections of regions for various θ_j can by determined and robustness with respect to some sensor and actuator failures can be achieved. Techniques for fixing some gains and some eigenvalues in a design step are developed in order to make graphical tradeoffs between

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two parameters at a time (versus only one parameter on a root locus). Design in K space also allows us to take control input constraints into account by minimizing a norm of K.

For circular λ-boundaries (as they arise in discrete time problems) general necessary conditions in form of a polyhedron in K space have been found. The calculation of the vertices of the polyhedron is surprisingly easy.

This design tool has been applied to the design of an aircraft control system for an F4E, which is destabilized by horizontal canards [60]. Military specifications for eigenvalue locations are met under widely varying flight conditions and accelerometer or gyro failures.

19.17 Chained Aggregation*

A new method of model reduction, based on the system output information structure, has been developed. The method is called chained aggregation [61]. The objective is to convert the system to the generalized Hessenberg Representation (GHR). This representation is then used directly to provide candidate reduced order models when the system is aggregable with respect to the actual outputs, or other aggregate variables, and to provide approximate reduced order models when the system is not aggregable. The chained aggregation procedure, the Generalized Hessenberg Representation, and their use in reduced order modeling are described in [61,62,63].

The generalized QL algorithm (QL) and the restricted QL algorithm (RQL) have been developed for adjustment of some parameters in candidate models when the degree of approximation obtained by simply neglecting the term coupling the residual system to the aggregate is unacceptable. The end result is a model associated with a particular control agent in which the dynamics of the external system are simplified

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and the interconnections between the detailed subsystem model and the external system are suitably modified. The GQL and RQL algorithms are described in [63,64,65] and normalization of state variables to improve numerical stability is given in [66].

Aggregability may be induced by feedback from the states of the residual system. That is, although a given system is not aggregable, a system modified by partial state feedback may be. This study has related the concepts of chained aggregation, Generalized Hessenberg Representation, and feedback induced aggregation to the structural invariants of linear time-invariant system, and specifically, to the observable subspace, the maximal (A,B)-invariant subspace in the null space of the output, the (A,B)-controllability subspace and the invariant zeros [14].

These results are employed in the hierarchical decomposition of control tasks between the global controller (coordinator) and local controllers (subsystem controllers) in resolving control problems in interconnected systems. The hierarchical decomposition scheme decomposes the controls into three components. The first decomposes the system model into aggregate and residual subsystems by inducing aggregation using feedback from the residual states. The second component, using only the states of the aggregate, solves the control problem associated with the aggregate system dynamics. The third component, using only states of the residual, shapes its dynamics subject to the constraint to not recouple the residual and aggregate. A paper describing this hierarchical control is in preparation.

19.18 Energy Conservation and Induced Inflation*

One frequently cited proposal for conserving energy calls for imposing a use tax to raise its <u>relative</u> price. The higher relative price of energy directly reduces the <u>final</u> demand for energy and also reduces the <u>intermediate</u> demand by inducing a more energy efficient technology. These savings resulting from reduced intermediate demand are produced by the substitution of other inputs for the higher priced energy.

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Un^fortunately the projected substitution is not sufficient to prevent a significant increase in the cost and therefore the price of many final products. These widespread price increases, in turn, stimulate wage increases, and these result in a more or less permanent boost in the inflation rate.

This induced inflation can be partially or wholly avoided by subsidizing the cost of the other (non-energy) goods. The most practical subsidy scheme appears to be a reduction in the general excise (or value added) tax. This reduction can be funded in large part by revenues generated by the use tax on energy. (This energy tax rebate is also attractive because it precludes any significant reduction in private aggregate demand which would otherwide be implied.)

A mathematical model of the flexprice-fixprice type which incorporates the major elements of the problem identified above has been developed. Representative estimates of the parameters of that model have been obtained. Simulation results generated by subjecting the model to a Newton-Ricatti optimization procedure. One simulation identifies the potential inflation generated by tax policies designed to induce a more energy efficient technology. It also suggests how much energy can be conserved by adopting this technology. A second simulation indicates how this potential inflation can be reduced or eliminated by a planned reduction in excise or sales taxes. This simulation also identifies the costs of this anti-inflation program.

Details of this work may be found in [67]. A journal article is also in preparation.

19.19 Adaptive Observers for Economic Models*

The continuous-time adaptive observer of Kreisseleiier [68, 69,70] is being extended to discrete-time systems. Theoretical conditions for convergence are being investigated. Experiments using simulated economic models are being undertaken to study the effectiveness of the method in an economic setting.

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19.20 Generalized Singularly Perturbed and Descriptor Variable Systems*

It has been shown that some systems exhibiting time scale separation properties are most naturally modeled as singularly perturbed systems which are not in any of the standard forms studied heretofore. The existence of such systems motivates the formulation of a more general singularly perturbed model. Such a model has been developed and a new canonical decomposition theorem established which decouples the generalized singularly perturbed system into slow and fast parts. Also, a sufficient condition has been found for convergence of the optimal control in the LQ regulator problem.

Since the limit of a singularly perturbed system is a description variable system, a study of the latter is an essential part of this work. Descriptor variable theory is considered from a geometrical point of view. A time-domain characterization of controllability and related results in the area of linear feedback and pole placement were obtained.

19.21 Multimodeling by Singular Perturbations†

Our multimodeling approach attempts to describe realistic situations in which the decision makers in a large scale system use different simplified models of the same system. An example is a multi-area power system. The decision maker in one area uses a detailed model of his area and only some lower order "equivalents" of the neighboring areas. The decision makers in other areas behave in a similar way and as a result each has his own view of the same large scale system. The strategies designed with such inconsistent models are then applied to the actual system.

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The purpose of this research is to investigate the effect of the multimodeling inconsistencies on the design and implementation of control strategies. The method is perturbational. If the model inconsistencies are small it is natural to require that their effect of the designed strategies and on the actual system performance be in some sense small. If this were not the case, the designed strategies would not be applicable to realistic systems whose models are never exactly known. We consider this low sensitivity property a sine qua non condition for any control design and, in particular, for the design of large scale systems controlled from multiple control stations.

Another fundamental property of our perturbational method is that it concentrates on modeling errors caused by reducing the model order. Such order reductions are achieved by separating the time scales, that is by considering slow and fast phenomena separately. A typical situation is when the decision maker in one area neglects the fast phenomena in all other areas. In geographically dispersed systems this practice is based on the experimental observation that faster phenomena propagate to shorter distances than the slower phenomena. For example, in a multimachine transient the slower oscillatory modes are observed throughout the system, while faster intermachine oscillations are of a more local character.

A tool for analyzing the change in model order is the so-called singular perturbation method which converts the change of model order into a small parameter perturbation. This parameter multiplies the derivatives of the fast state variables and when it is zero the fast phenomena are neglected. They are then separately reintroduced as the so-called "boundary layers."

An earlier design method based on time scale separation developed in [71] serves as a prototype for more complex multicontroller [72-75] and nonlinear designs [76-78].

The multimodeling results are summarized in [72-75]. The main assumption that each decision maker knows only his simplified model of the full system is formalized in [72]. This simplified model is obtained by neglecting the small parameters in all other subsystems. In [72] an additional assumption is made that the fast parts of different subsystems

are weakly coupled. Under this assumption the multimodel design of feedback regulators is shown to be stabilizing and near optimal. To remove the assumption of weakly interacting fast subsystems a deeper investigation is undertaken in [73] and [74]. A new sufficient condition called "block D-stability" is derived which generates several practical tests for multiparameter boundary layers. The relationship of this condition with multiple-time scales is then examined in [74]. The main result of [74] is a procedure for including limited, not necessarily weak, interactions of fast subsystems. These fundamental results represent a new formulation of the large scale system modeling problem. They are applied to a decentralized design in [75].

The main accomplishment in the nonlinear regulator design is the possibility of a separation of slow and fast designs [76, 78] for a wide class of systems, including synchronous machines [77]. Moreover, a region of asymptotic stability is guaranteed even in the critical case, that is when linearization fails to predict stability properties [76].

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20. POPULATION/FOOD/WEATHER STUDIES*

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20.1 Introduction

a. This program is concerned with the use of computer-generated graphics in teaching a number of interrelated disciplines dealing with population. Under this program for the NSF, we are distributing the DEMO-GRAPHICS software to universities and colleges throughout the USA. The purpose is to provide innovation in the teaching of these subjects through the use of computers. Thus far, the population program has been introduced into more than 75 universities and colleges and has been used in many classes and demonstrations. This coming fall the material will probably be used by thousands of students.

The mode of information transfer is primarily through the use of computer-generated graphics and also includes the use of other types of visual materials, such as slides, transparencies, and booklets derived from the computer-generated graphics. In addition, user manuals, teachers' guides and other printed materials are also available. The programs are now running on a number of computer systems and are almost machine independent, thus enabling wide use. We plan to extend the use of the materials to additional educational institutions and to many other disciplines. We have conducted a number of workshops for teachers and graduate students as an introduction in the use of DEMO-GRAPHICS in their various disciplines.

b. A second program is concerned with developing long range forecasting techniques for weather and climate. The forecast range varies from a few months to a few years. In addition to the common meteorological variables, crop data has been found to be a useful indicator of long range weather trends.

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20.2 Distribution

The programs have been distributed to 75 colleges and universities, 8 high schools and 9 other institutions. Over 1200 students have used the programs in the spring semester in 16 different disciplines.

20.3 Long Range Weather Forecasting

During the past two years a new program has been initiated to determine whether it is possible to develop a system which would allow one to forecast climate or weather six months to two years in advance. Some preliminary success has been obtained using worldwide crop production and yield data as well as a number of unique meteorological variables. The program has been relatively successful in that a number of predictions have been made which have, in fact, occurred. While the program is still in its infancy, we hope by including additional variables and new mathematical techniques that we will be able to improve the reliability of the forecasts to the point where they will become an important tool in long range weather forecasting.

APPENDIX A

SUMMARY OF TRAVEL

Date of Travel	Personnel	Places of Visit	Purpose
6/4-6/7/78	J. B. Cruz, Jr.	Kingston, Rhode Island	To participate in the Kingston Conference on Differential Games.
6/25-7/1/78	M. B. Pursley	Lake Tahoe, California	To participate in the IEEE Information Theory Workshop.
6/26-6/29/78	John Leap	Ottawa, Ontario, Canada	To present a paper entitled "Two Phonon Pumping of a 4-Level System in Ammonia to Obtain 12.16 (μm) Radiation for Isotope Separation" at the IEEE MTT Microwave Symposium.
8/5-8/9/78	J. E. Greene	Andover, New Hampshire	To present a paper entitled "Ion Bombardment Enhanced Diffusion" at the Gordon Research Conference.
8/13-8/16/78	Mark Etzel	Ames, Iowa	To participate in the 21st Midwest Symposium on Circuits & Systems.
8/13-8/16/78	W. K. Jenkins	Ames, Iowa	To present papers entitled "New Structures for Switched Capacitor Sampled-Data Filters" and "Architectures for Micro-Processor-Based Adaptive Digital Filters" at the 21st Midwest Symposium on Circuits & Systems.
8/21-8/26/78	J. E. Greene	Andover, New Hampshire	To present a paper entitled "Plasma Etching of Si" at the Gordon Research Conference.
9/17-9/20/78	D. V. Sarwate	Provincetown, Massachusetts	To present a paper entitled "Cross-Correlation Properties of Sequences with Applications to Spread-Spectrum Multiple Access Communications" at the AFOSR Workshop in Communication Theory and Application.

SUMMARY OF TRAVEL (continued)

Date of Travel	Personnel	Places of Visit	Purpose
8/21-8/25/78	Blake E. Cherrington	Boston, Massachusetts	To present a paper entitled "Modeling of Low Pressure Rare Gas Discharges, Laser and Microwave Diagnostics of *Plasmas*" at the Gordon Research Conference.
8/22-8/25/78	Joel Emer	Traverse City, Michigan	To present a paper entitled "Control Store Organization for Multiple Stream Pipelined Processing" at the ACM/IEEE International Conference on Parallel Processing.
9/17-9/19/78	T. N. Trick	Timberline, Oregon	To attend a Workshop on Integrated IC Design Aids sponsored by the Circuits and Systems Society of the IEEE.
9/18/78	Charles Wickersham	Dallas, Texas	To present a paper entitled "The Effect of Substrate Bias on the Electrical and Optical Properties of RF Sputtered In_2O_3 Films" at the American Ceramics Society Conference.
9/19-9/20/78	M. B. Pursley	Provincetown, Massachusetts	To present a paper entitled "Mismatch Bounds for Variable Rate Source Codes with Applications to Universal Data Compression" at the AFOSR Workshop in Communication Theory and Applications.
9/23-9/28/78	Michael Hoskins	Cherry Hill, New Jersey	To present a paper entitled "Line Acoustic Waves on Cleaved Edges in $LINBO_3$ and GaAs" at the IEEE Conference on Sonics and Ultrasonics.
9/24-9/27/78	S. Modesti	St. Louis, Missouri	To participate in the 7th Symposium on GaAs and Related Components.
9/24-9/27/78	T. Hua Yu	St. Louis, Missouri	To participate in the 7th Symposium on GaAs and Related Components.

SUMMARY OF TRAVEL (continued)

Date of Travel	Personnel	Places of Visit	Purpose
9/24-9/27/78	B. G. Streetman	St. Louis, Missouri	To present a paper entitled "Planar Ion-Implanted Avalanche Photodiodes in GaAs" at the 7th Symposium on GaAs and Related Components.
9/24-9/27/78	Ding-Yuan Day Max Helix	St. Louis, Missouri	To present a paper entitled "Planar Ion-Implanted Avalanche Photodiodes in GaAs" at the 7th Symposium on GaAs and Related Components.
9/26-9/29/78	J. A. Abraham	Atlanta, Georgia	To present a paper entitled "An Approach to the Design of Large Fault-Tolerant Systems" at the Workshop on Fault-Tolerant System Design and Implementation.
9/30/78-1/2/79	Hadis Morkoç	Murray Hill, New Jersey	To conduct research in Molecular Beam Epitaxy with Dr. A. Y. Cho at Bell Labs in connection with the new JSEP MBE research program at CSL.
10/15-10/17/78	Sowmitri Swamy	Ann Arbor, Michigan	To participate in the IEEE Symposium on Foundations of Computer Science.
10/15-10/17/78	F. P.Preparata	Ann Arbor, Michigan	To participate in the IEEE Symposium on Foundations of Computer Science.
10/15-10/17/78	Donna J. Brown	Ann Arbor, Michigan	To participate in the IEEE Symposium on Foundations of Computer Science.
10/16-10/20/78	Blake E. Cherrington	Buffalo, New York	To participate in the 31st Gaseous Electronics Conference.
11/5-11/8/78	W. K. Jenkins	Pacific Grove, California	To present a paper entitled "New Experimental Circuits for Switched Capacitor Filters" at the 12th Annual Asilomar Conference on Circuits, Systems & Computers.

SUMMARY OF TRAVEL (continued)

Date of Travel	Personnel	Places of Visit	Purpose
11/5-11/9/78	Wataru Mayeda	Pacific Grove, California	To present a paper entitled "Reduced-Order Modeling Through Successive Approximation" at the 12th Annual Asilomar Conference on Circuits, Systems & Computers.
11/5-11/9/78	A. H. Haddad	Pacific Grove, California	To present a paper entitled "A Detection-Estimation Approach to State Estimation in Switching Environments" at the 12th Annual Asilomar Conference on Circuits, Systems and Computers.
11/15-11/16/78	R. T. Chien	Chicago, Illinois	To present a paper entitled "Semantic Models and Computerized Decision Making" and chair a session at the COMPSAC Conference.
11/19-11/23/78	B. R. Rau	Monterey & Stanford, California	To present a paper entitled "Levels of Representation of Programs and the Architecture of Universal Host Machines" at the 11th Annual IEEE Workshop on Microprogramming; to discuss research with Prof. Flynn of Stanford University.
11/28-12/1/78	Lindley Specht	Madison, Wisconsin	To participate in the Electron and Atomic Physics Conference.
12/4-12/6/78	David Borth	Birmingham, Alabama	To present a paper entitled "Direct-Sequence Spread-Spectrum Multiple-Access Communication for a Class of Rician Fading Channels" at the National Telecommunications Conference.
12/4-12/6/78	M. B. Pursley	Birmingham, Alabama	To present a paper entitled "Direct-Sequence Spread-Spectrum Multiple-Access Communication for a Class of Rician Fading Channels" at the National Telecommunications Conference.

SUMMARY OF TRAVEL (continued)

Date of Travel	Personnel	Places of Visit	Purpose
12/12-12/14/78	Raj Mittra	New York, New York	To attend the JSEP Review at the Polytechnic Institute of New York.
12/13-12/14/78	J. Ackermann J. B. Cruz, Jr. Douglas Looze W. R. Perkins	St. Louis, Missouri	To discuss research with officials at McDonnell-Douglas.
1/6-1/12/79	A. H. Haddad	San Diego, California	To present papers entitled "Asymptotic Analysis of a Class of Nonlinear Filtering. Part 1: A Generic Example" and "State Estimation Under Uncertain Observations with Unknown Statistics" at the IEEE Conference on Decision and Control.
1/8-1/12/79	W. R. Perkins	San Diego, California	To participate in the IEEE Conference on Decision and Control.
1/7-1/12/79	Douglas Looze	San Diego, California	To participate in the IEEE Conference on Decision and Control and the 1st International Symposium on Mini and Microcomputers in Control.
1/8-1/12/79	J. B. Cruz, Jr.	San Diego, California	To participate in and chair a session at the IEEE Conference on Decision and Control.
1/8-1/12/79	H. V. Poor	San Diego, California	To present a paper entitled "Some Results in Robust Wiener Filtering" at the IEEE Conference on Decision and Control.
1/28-1/30/79	Sowmitri Swamy	San Antonio, Texas	To present a paper entitled "Space-Time Tradeoffs for Linear Recursion" at the 6th International ACM Conference on Principles of Programming Languages.

SUMMARY OF TRAVEL (continued)

Date of Travel	Personnel	Places of Visit	Purpose
2/4-2/9/79	R. T. Chien	Los Angeles, California	To attend JSEP Research Reviews at the University of Southern California and the California Institute of Technology.
2/18-2/20/79	Karl Hess	Atlanta, Georgia	To participate in the Conference on Microwave Devices and to discuss research with Dr. Horst Wittmann of the Army Research Office.
2/18-2/20/79	Hadis Morkoç	Atlanta, Georgia	To present a paper entitled "Cr-Doped GaAs and $Al_xGa_{1-x}As$ Layers as Buffers for FET's Grown by MBE" at the Workshop on Compound Microwave Semiconductor Materials and Devices.
2/18-2/21/79	Gregory Stillman	Atlanta, Georgia	To present a paper entitled "High-Purity InP Grown by the Hydride Process" at the Workshop on Compound Semiconductor Microwave Materials.
2/27-3/1/79	Jacob Abraham	San Francisco, California	To present a paper entitled "User Testing of Microprocessors" at the IEEE COMPCON '79.
3/18-3/22/79	R. Merlin	Chicago, Illinois	To participate in the March Meeting of the American Physical Society.
3/28-3/30/79	H. V. Poor	Baltimore, Maryland	To present papers entitled "On Detection in Weakly Dependent Noise" and "A Comparison of Some Robust Detectors for Stochastic Signals" at the Johns Hopkins Conference on Information Sciences and Systems.
3/27-4/1/79	Donna J. Brown	Baltimore, Maryland	To present a paper entitled "Lower Bounds for on-Line Two-Dimensional Packing Algorithms" at the Johns Hopkins Conference on Information Sciences and Systems.

SUMMARY OF TRAVEL (continued)

Date of Travel	Personnel	Places of Visit	Purpose
4/3-4/7/79	R. T. Chien	Philadelphia, Pennsylvania	To present a paper entitled "Motion Detection and Analysis with Intermediate-Level Primitives" and chair a session at the Workshop on Computer Analysis of Time-Varying Imagery.
4/4-4/7/79	Michael Selander Charles Jacobus	Philadelphia, Pennsylvania	To present a paper entitled "Motion-Detection and Analysis with Intermediate-Level Primitives" at the Workshop on Computer Analysis of Time-Varying Imagery.
4/24-4/28/79	J. A. Abraham	Denver, Colorado	To present a paper entitled "Issues in Processor Testability" at the 1979 IEEE Workshop on Design for Testability.
4/24-4/28/79	Gernot Metze	Denver, Colorado	To present the Keynote Address at the IEEE Workshop on Design for Testability and visit and discuss research with officials at Hewlett-Packard.
4/29-5/2/79	Donna J. Brown	Atlanta, Georgia	To participate in the ACM Symposium on the Theory of Computers.
5/7-5/10/79	Hadis Morkoç	Boston, Massachusetts	To present a paper entitled "High Purity and Cr Doped GaAs by MBE" at the Annual Meeting of the Electrochemical Society.
5/7-5/10/79	Andrew White	Chicago, Illinois	To present a paper entitled "Design Considerations for Teleconferencing Systems" at the Society for Information Display International Symposium 1979.
5/22-5/25/79	Douglas Looze	Montreal, Canada	To present a paper entitled "Analysis of Hierarchical Decomposition Algorithms Via Nonlinear Splitting Functions" at the Optimization Days Conference.

Date of Travel	Personnel	Places of Visit	Purpose
5/23-6/23/79	Hadis Morkoç	Newark, New Jersey	To conduct research at Bell Laboratories with Dr. A. Y. Cho on Molecular Beam Epitaxy in connection with the new JSEP MBE research program at CSL and to attend the American Vacuum Society Conference.
5/30-6/1/79	Douglas Looze	Boston, Mass.	To discuss mutual research with scientists at MIT.
6/15-6/19/79	Ibrahim Hajj	Philadelphia, Pennsylvania	To present a paper entitled "Large-Change Sensitivity Computation and Partitioning" at the 22nd Midwest Symposium on Circuits and Systems.
6/15-6/19/79	Douglas P. Looze	Philadelphia, Pennsylvania	To present a paper entitled "Local Analysis and Comparison of Hierarchical Control Systems" at the 22nd Midwest Symposium on Circuits and Systems.
6/17-6/19/79	M. B. Pursley	Seattle, Washington	To present a paper entitled "Large Time-Bandwidth Product Signals for Spread-Spectrum Multiple-Access Communications" at the IEEE/APS International Symposium and National Radio Science Meeting.
6/19-6/22/79	Jacob Abraham	Madison, Wisconsin	To present a paper entitled "Test Generation for General Micro-Processor Architectures" at the 9th International Symposium on Fault-Tolerant Computing.
6/20-6/22/79	Gernot Metze	Madison, Wisconsin	To participate in the Fault-Tolerant Computing Symposium and also serve as a session chairman.